12-2015

Use of HPPD-inhibiting herbicides for control of common weeds in Arkansas and current status of herbicide-resistance among Echinochloa populations in Arkansas

Clay Starkey
University of Arkansas, Fayetteville

Use of HPPD-inhibiting herbicides for control of common weeds in Arkansas and current status of herbicide-resistance among *Echinochloa* populations in Arkansas

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil, and Environmental Science

by

Clay E. Starkey
Southern Illinois University Carbondale
Bachelor of Science in Agribusiness Economics, 2009

December 2015
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

Dr. Nilda R. Burgos Co-Thesis Director	Dr. Jason K. Norsworthy Co-Thesis Director
Dr. Robert C. Scott Committee Member	Dr. Kristofor Brye Committee Member
Dr. Andronikos Mauromoustakos Committee Member	Mr. Alan Hopkins (E*x-offico Committee Member*)

Abstract

Herbicide-resistant weeds in Arkansas cause problems for growers. Up-to-date information and new technologies can help plan mitigation strategies to slow resistant weeds. The objectives of this research were to provide a 'snapshot' of herbicide-resistant *Echinochloa* spp. in rice producing counties, determine how much resistance has spread across the state, and understand the effectiveness of 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides for control of glyphosate-resistant (GR) Palmer amaranth relative to commercial standards currently labeled in soybean. To assess the prevalence of *Echinochloa* spp. resistance, 82 samples were collected from 23 rice producing counties in 2010. The samples were tested for resistance to commonly used rice herbicides: propanil, quinclorac, imazethapyr, fenoxaprop, clomazone, and glyphosate. Of the 82 samples collected, 29 were resistant to propanil, 13 were resistant to quinclorac and 9 samples were resistant to both propanil and quinclorac. Accessions were also treated with 0.5x the labeled field rate for glufosinate and isoxaflutole to determine background variation in sensitivity among populations to these herbicides as *Echinochloa* is among the major weeds in crops where these herbicides are used. No resistance to imazethapyr, clomazone, fenoxaprop, or glyphosate was observed; likewise all accessions were sensitive to glufosinate or isoxaflutole. One strategy for controlling herbicide-resistant weeds is the use of transgenic crops. The expected release of soybean in 2016 and cotton in 2020 with resistance to HPPD-inhibiting herbicides provide alternative mechanisms-of-action to control weeds. Experiments were conducted in 2010 and 2011 to determine the efficacy of HPPD-inhibiting herbicides as a preemergence (PRE) option for *Echinochloa* spp. and Palmer amaranth control

and as a postemergence (POST) option with and without glyphosate or glufosinate. The PRE applied HPPD-inhibiting herbicides do not carry the residual control as the current industry standards; however they are still capable of providing 4 weeks of control of Palmer amaranth and *Echinochloa* spp.. For both years in the POST trials, all treatments, except glyphosate alone, provided >90% control of 2.5- to 10-cm tall GR-Palmer amaranth at 3 wk after treatment. When herbicides were applied to larger Palmer amaranth, 15- to 25-cm tall, control with isoxaflutole + glyphosate, tembotrione + glufosinate, and tembotrione + glyphosate were greater than 90%. Applications made to Palmer amaranth larger than 25 cm was not effective (< 80% control).

Acknowledgements

I would like to start by thanking my parents Jeffery and Connie Starkey. They knew I was capable of my best in times when I was less than sure. The support that they showed me through my education has been everything I needed even when separated by 500 miles. Whether a phone call at night or a weekend trip to the lake, I knew I always had that special support that only a parent could give.

My gratitude to Dr. Nilda Burgos or Dr. Jason Norsworthy is far beyond any appreciation I can put in writing. Through these advisors I was allowed the opportunity for a great education and diversity through my time at the University of Arkansas. Nothing could have prepared me for the unexpected experience that I found in the weed science program. From grueling weed team, downstate trips, and spending hours in the lab have all provided me the adaptability and diversity to succeed in life.

To Justin DeVore, Pratap Devkota, Griff Griffith, Brent Johnson, Sandeep Rana, and Josh Wilson: I owe you guys a lot for all the challenging times we had on our down state trips or across the road. Also, for taking me in and letting me feel welcomed in Arkansas when I did not know anyone. I owe each of you many favors.

The reason I had the opportunity to attend Arkansas is because of Bayer CropScience, especially Richard Rudolph. To you I am grateful for the program that was established and my goal is to be able to follow in your footsteps and pass on the same opportunities I was afforded.

To my committee members, I would like to thank all of you for taking the time to speak with me either on the phone or one-on-one to provide me with the many educational and insightful perspectives regarding my research and personal experiences.

Table of Contents

List of Tables

Chapter 1

Chapter 2

List of Figures

Chapter 1

Appendices

Chapter 1

Chapter 2

Use of HPPD-Inhibiting Herbicides for Control of Common Weeds in Arkansas and the Status of Herbicide-Resistance Among *Echinochloa* Populations in Arkansas

Clay E. Starkey

General Introduction

Weeds reduce both crop productivity and quality by competing for nutrients, light, and water ultimately affecting the world's demand for agricultural products. Weed control is accomplished through various methods including mechanical, cultural, biological, and chemical. Herbicides are major weed control tools and have been effective for the removal of most weeds from major row crops such as soybean [*Glycine max* (L.) Merr.], cotton (*Gossypium hirsutum* L.), and rice (*Oryza sativa* L.). Fueled by ease of application and effectiveness, herbicide use has dramatically increased from the 1950s to today (Young 2006). The most effective herbicides are often overused, leading to the evolution of resistant biotypes (Tranel and Wright 2002). Currently there are more than 430 weed biotypes which have evolved resistance to herbicides (Heap 2014).

Prior to 1995, regulations and uncertainties prevented transgenic crops from being commercialized and used globally. In 1995, transgenic cotton with resistance to bromoxynil was deregulated. Although bromoxynil was an effective tool for some weeds in cotton, bromoxynil was not an economical solution and did not provide broad-spectrum weed control (Duke and Cerdeira 2005). One benefit of bromoxynil-resistant cotton was that it served as the first deregulated, transgenic crop in the U.S. and later became commercialized, paving the way for deregulation and commercialization of other transgenic crops. Perhaps the greatest breakthrough in transgenic crops came with the commercialization of glyphosate-resistant soybean and canola (*Brassica napus* L. and *B. rapa* L.) in 1996.

Glyphosate is a non-selective herbicide that provides broad-spectrum weed control, relatively inexpensive, and easily degraded by soil microorganisms. Deregulation of glyphosate-resistant canola and soybean in 1996 was followed by cotton, corn, sugarbeet (*Beta vulgaris* (L.), and alfalfa *Medicago sativa* (L.) in 1997, 1998, 1999, and 2005, respectively (Duke and Powles 2009). The effectiveness of glyphosate on weeds in glyphosate-resistant crops provided growers with a single, effective herbicide mechanism-of-action. In Arkansas, cotton producers made at least two applications of glyphosate on 98% of all fields with three or more applications on at least 95% of these fields (Norsworthy et al. 2007b). The continued use of glyphosate with minimal use of additional herbicides in Arkansas row crops has selected for glyphosate resistance in six weed species; horseweed (*Conyza canadensis* L Cronquist), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), Palmer amaranth (*Amaranthus palmeri* S. Wats.), johnsongrass (*Sorghum halepense* L. Pers.), and Italian ryegrass (*Lolium perenne ssp. multiflorum*) (Heap 2014).

Glufosinate-resistant canola, corn, cotton, and soybean were commercialized in 1995, 1996, 2004, and 2008, respectively. By the time glufosinate-resistant cotton and soybean were released, glyphosate-resistant cotton and soybean was already widely adopted. Glufosinate became an option for controlling glyphosate-resistant weeds and those with natural tolerance to glyphosate.

Two of the most problematic resistant weeds in Arkansas crop production are barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and Palmer amaranth. Although integrated weed resistance management practices have been strongly recommended, growers have relied on easy and short-term economical control methods making multiple applications of the same herbicides (Talbert and Burgos 2007). Palmer amaranth and barnyardgrass have become more difficult to control and an increasing concern in recent years as a result of evolved resistance to several herbicide mechanisms of action (Webster and Nichols 2012; Norsworthy et al. 2007a).

Mitigating the evolution of herbicide resistance requires a better understanding of how resistance evolves, spreads, and how to effectively control resistant biotypes. A 2006 survey of consultants in Arkansas showed that 92 and 94 percent of those surveyed were concerned with resistance issues in rice and cotton, respectively (Norsworthy et al. 2007a; Norsworthy et al. 2007b). Education, extension, and outreach activities are credited for the increase of awareness to resistance; however, further education and methods of control are required; hence, research was conducted to evaluate control of Palmer amaranth and *Echinochloa* spp. using new herbicide-trait technologies and to provide a ‘snapshot’ view of herbicide-resistant *Echinochloa* spp. in Arkansas’ rice-producing counties in 2010.

Literature Cited

Coetzer EK, Al-Khatib K, Loughin TM (2001) Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. Weed Sci 49:1-13

Duke SO, Powles SB (2009) Glyphosate-resistant crops and weeds: Now and in the future. 3 & 4:246-357

Duke SO, Cerdeira AL (2005) Potential Environmental Impacts of Herbicide-Resistant Crops. Collection of Biosafety Reviews 2:66-143

Heap I (2014) International survey of herbicide resistant weeds. http://www.weedscience.org Accessed June 3, 2014

Norsworthy JK, Burgos NR, Scott RC, Smith KL (2007a) Consultant perspectives on weed management needs in Arkansas rice. Weed Technol 21:832-839

Norsworthy JK, Smith KL, Scott RC, Gbur EE (2007b) Consultant perspectives on weed management needs in Arkansas cotton. Weed Technol 21:825-831

Talbert RE and Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324-331

Tranel PJ, Wright TR (2002) Resistance of weeds to ALS-inhibiting herbicides: What have we learned? Weed Sci 50:700-712

Young, BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307

Webster TM, Nichols RL (2012) Changes in the prevalence of Weed Species in the Major Agronomic Crops of the Southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145-157

Chapter 1

Response of Arkansas *Echinochloa* spp. Accessions to Common Rice Herbicides

Abstract

Many herbicide-resistant populations have inundated rice producers since the early 1990s. Propanil-, quinclorac-, clomazone-, and ALS herbicide-resistant *Echinochloa* spp. have all been documented in Arkansas. The objectives of this research were to portray a spatial distribution of herbicide-resistant *Echinochloa* spp. in Arkansas and determine options for producers to control these resistant accessions. Another objective was to assess variation in baseline tolerance to herbicides used as a pre-plant burndown treatment or in other crops where *Echinochloa* is also a problem. Eighty-two accessions of *Echinochloa* spp. were either collected or submitted for screening from 23 rice-producing counties in Arkansas. Accessions were treated postemergence (POST) with the labeled field rates of propanil (4,480 g ai ha^{-1}), quinclorac (564 g ai ha^{-1}), imazethapyr (105 g ai ha^{-1}), fenoxaprop (86 g ai ha^{-1}), and glyphosate (870 g ae ha^{-1}) as well as preemergence (PRE) with clomazone (336 g ai ha^{-1}). Accessions were also treated with a 0.5x rate of either glufosinate (240 g ai ha^{-1}) or isoxaflutole (53 g ai ha^{-1}) to determine differentiation in baseline tolerance and detect accessions with high propensity to evolve resistance. All accessions were visually rated for phytotoxicity and mortality. Accessions were considered resistant when the control was below 70%. Eleven of the 23 counties sampled had 29 accessions resistant to propanil. Quinclorac resistance was observed in 13 accessions from 11 counties. Of the 13 samples that were resistant to quinclorac, 9 (from 7 counties) were also resistant to propanil. No resistance was observed to clomazone, imazethapyr, fenoxaprop, or glyphosate. Accessions did not differ in control when treated with a 0.5x rate of glufosinate or isoxaflutole.

Nomenclature: Fenoxaprop; glufosinate; glyphosate; imazethapyr; isoxaflutole; propanil; quinclorac; *Echinochloa crus-galli* L. Beauv.; *Echinochloa* spp.; rice, *Oryza sativa* L.

Key words: Herbicide resistance screening, herbicide resistance distribution

Introduction

Herbicides have been an effective control method for weeds in rice, the most commonly grown cereal in Arkansas. When producers are offered a herbicide that is economical and effective, its use is often extensive. Because of the overuse of herbicides with the same mechanism of action, resistant biotypes evolved (Heap 2014; Tranel and Wright 2002). The most problematic herbicide-resistant weed in Arkansas rice production is barnyardgrass (Norsworthy et al. 2007a). Follow-up research has shown that a mixture of *Echinochloa* species primarily junglerice (*E. colona*) and barnyardgrass (*E. crus-galli*), occur in many fields. Because species identities were not verified when this experiment was conducted, the collective term *Echinochloa* spp. will be used here, except when specifically discussing a particular species. Mitigating the evolution of resistance requires a better understanding of how resistance evolves and spreads and how to effectively control resistant biotypes. This researched focused on generating the resistance profiles of *Echinochloa* spp. in Arkansas.

Barnyardgrass is a semi-aquatic weed from the family Poaceae and causes yield loss in many crops grown in Arkansas. Known as the "world's principal weed of rice" (Mitich 1990), barnyardgrass has been and continues to be the most troublesome weed in rice production (Norsworthy et al. 2007a; Smith 1974). Barnyardgrass can reduce rice yield up to 80% (Smith 1968). The extensive use of herbicides in U.S. rice production has led to barnyardgrass evolving resistance to four of the most commonly used herbicide mechanisms of action in Arkansas rice: inhibitors of photosynthesis at photosystem II site A , acetolactate synthase (ALS) inhibitors, synthetic auxins, and 1-deoxy-D-xyulose 5-phosphate synthase (Carey et al. 1995; Heap 2014; Malik et al. 2010; Norsworthy et al. 2007b; Talbert and Burgos 2007; Wilson et al. 2010).

Understanding the process of evolution and spread of resistance is crucial to hinder further expansion of the problem. Resistance management publications (Bagavathiannan et al. 2013; Scott et al. 2009) and meetings have conveyed this message across Arkansas as evidenced by 92% of rice consultants being concerned with herbicide resistance issues (Norsworthy et al. 2007a). Effective weed management programs are of high priority in rice in Arkansas and around the world. Currently, there are 23 countries worldwide affected by herbicide-resistant barnyardgrass (Heap 2014). Educating consultants and extension agents on how to control resistant weeds and reduce selection for resistance will help to preserve many of the herbicides and technologies used in rice production today.

In the early 1960s, propanil was the sole herbicide used for POST control of barnyardgrass in rice (Smith 1965). The ability of rice to metabolize propanil and propanil's effective control of barnyardgrass, provided producers an effective selective herbicide option for this troublesome weed (Yih et al. 1968). By the early 1990s, the efficacy of propanil, along with propanil being the only available option for POST control of barnyardgrass in rice, had Arkansas rice producers applying the herbicide to 98% of all rice hectares (Carey et al. 1995). Carey et al. (1995) first found resistance to propanil in Arkansas in 1990. Propanil-resistant barnyardgrass was able to metabolize propanil to 3'4-dichloroaniline (DCA) through the same metabolic process as rice, whereas propanil-susceptible barnyardgrass has a slower oxidative metabolism thus creating a buildup of propanil at lethal doses (Carey et al. 1997; Yih et al. 1968). In 2006, a survey of crop consultants in Arkansas estimated that 24% of the rice hectares in Arkansas were infested with propanil-resistant barnyardgrass (Norsworthy et al. 2007a).

Quinclorac is an effective herbicide that has a different mechanism of action than that of propanil and can control propanil-resistant barnyardgrass (Baltazar and Smith 1995). Producers started using quinclorac extensively in 1992; by 1999, quinclorac-resistant barnyardgrass biotypes were documented and soon became as problematic as the propanil-resistant biotypes, although not as widespread. With propanil and quinclorac being the cornerstone of weed control in rice, it was inevitable that resistance to both propanil and quinclorac would evolve, which was confirmed in 1999 (Lovelace et al. 2000). In 2006, it was estimated that 7% of Arkansas rice was infested with quinclorac-resistant barnyardgrass (Norsworthy et al. 2007a). Resistance to propanil and quinclorac resulted in limited POST options for *Echinochloa* spp. control in rice.

Another option for weed control in rice is the application of herbicides prior to weed emergence (preemergence, PRE). An effective PRE herbicide for *Echinochloa* spp. control is clomazone from the isoxazolidinone chemical family, representing yet another mechanism-of-action. In the survey conducted by Norsworthy et al (2007a), 93% of consultants who recommended a PRE application in rice recommend clomazone. Thus, selection pressure with this herbicide mechanism-of-action intensified quickly. In 2007, as with the other herbicides propanil and quinclorac, clomazone-resistant barnyardgrass was discovered in Arkansas (Norsworthy et al. 2008).

One alternative management tool is planting herbicide-resistant rice cultivars. Non-transgenic rice cultivars that are resistant to the imidazolinone family of herbicides (Tan et al. 2005), known as Clearfield® rice, were introduced in 2002. This herbicide family includes imazethapyr, which is effective for controlling *Echinochloa* spp. (Meier et al. 2010; Pellerin and Webster 2004). As the only POST-applied herbicide option for control of propanil- and quinclorac-resistant barnyardgrass, this technology was widely adopted and use increased to as much as 55 % of total rice acres in Arkansas by 2010 (Hardke and Wilson 2012), eventually leading to selection for imazethapyr-resistant barnyardgrass (Wilson et al. 2010; Riar et al 2012).

Proactive measures to slow resistance evolution among *Echinochloa* populations are greatly needed. Crop rotation is a key factor in controlling *Echinochloa* spp. effectively. It is expected that in 2016 transgenic soybean, and in 2020 transgenic cotton, with resistance to several 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides will be commercialized. The release of HPPD-resistant soybean and cotton is expected to increase the use of HPPD-inhibiting herbicides in Arkansas. The increasing adoption of glufosinate-resistant soybean, another transgenic crop, has led to an increase in the use of glufosinate for in-crop weed control. Measures to ensure that these technologies have not been compromised prior to widespread use are required to ensure longevity of these traits. Screening for variation in the response of *Echinochloa* spp. to these herbicides provides an early indication of the likelihood of resistance evolving to these families of herbicides.

The great magnitude of herbicide-resistant *Echinochloa* spp. is apparent in Arkansas. Proactive measures are needed to delay the onset of resistance. A distribution map of propanil- and quinclorac-resistant *Echinochloa* spp. in Arkansas was produced in 1991-92 (Carey et al. 1995). This research aimed to provide an updated distribution map of herbicide-resistant *Echinochloa* spp. populations in Arkansas and survey the occurrence of *Echinochloa* spp. with resistance to imazethapyr and clomazone, which are recent occurrences. This research also aimed to determine the variability in sensitivity of *Echinochloa* spp accessions to low rates of both glufosinate and isoxaflutole.

Materials and Methods

Survey of Resistance to Rice Herbicides. In the summer of 2010, *Echinochloa* spp accessions were collected from Arkansas rice fields. Eighty-two total samples were collected from 23 of the top 26 rice-producing counties in Arkansas (Table 1). Panicles from at least 20 plants were placed in paper bags and transported to the Altheimer Laboratory at the University of Arkansas, Fayetteville. All samples, except one, had corresponding GPS coordinates. Some samples had information on cropping herbicide history, but several did not have this information. Samples from extension agents and crop consultants were from fields with a failed herbicide application. Each accession was assigned a code number as they were collected or received (Appendix 1.1). Coordinates and field information were entered into JMP© Pro Version 9.0.0 JMP (Version 9.0.0. Copyright 2010 SAS Institute Inc.). Accessions were separated by 8 km, where possible, to represent separate *Echinochloa* spp. populations. However, because of samples received from consultants or Extension Agents, only 68 of the 82 samples met the 8-km criteria. Of the samples not meeting the separation criteria, none were closer than 2 km in separation with most at the 5 to 8 km distance. Each sample was threshed, and seeds were placed in a cool, dark room (about 15 C) for approximately 1 to 6 mo prior to planting to allow after-ripening (Martinkova et al. 2006).

Resistance assays were conducted at the University of Arkansas Altheimer Laboratory greenhouse in 2010 and 2011. Approximately 100 seeds were placed in a 12- by 12- by 5-cm pots filled with 3 cm of potting soil (Sunshine Mix®, Sun Gro Horticulture Inc., Bellevue, WA 98008). Following emergence, seedlings were thinned to approximately 25 plants per pot two days prior to herbicide application to allow recovery from root disturbance. Pots were arranged in a randomized complete block design replicated two times, and repeated, to evaluate a maximum of 100 plants per accession per treatment. Pots were irrigated daily, and greenhouse temperatures were maintained at 30/20 C day/night temperature with a 14-hr day length, supplemented with artificial light (500 µm m^{-2} s^{-1}). *Echinochloa* spp at the 2- to 3-leaf stage were counted for each pot. At this growth stage (5 to 8-cm seedlings), POST herbicides were applied including, imazethapyr at 105 g ai ha^{-1} + 0.25 % v/v non-ionic surfactant, propanil at 4,480g ai ha^{-1}, fenoxaprop at 86 g ai ha^{-1}, and quinclorac at 564 g ai ha^{-1} + 1% crop oil concentrate (COC). Sources of herbicides are listed in Appendix 2. Applications were made in a spray chamber equipped with a two-nozzle boom with 80067 flat-fan tips (TeeJet Spraying Systems Co., Wheaton, IL 60189) calibrated to deliver 187 L ha^{-1} at 276 kPa.

At predetermine times after herbicide application, the accessions were visually rated for phytotoxicity response on a 0 to 100% scale, where 0 was no injury and 100 was complete control. If 100% control was not achieved, the number of surviving plants per pot was recorded at1 week after treatment (WAT) for the fast-acting propanil (contact herbicide) and at 4 WAT for all other systemic herbicides. Each run of the assay was conducted with a susceptible accession for comparison (Azlin Seed Service Leland, MS 38756). Pots were monitored daily and any newly emerged plants were removed.

Screening for resistance to clomazone was conducted in the greenhouse. Two, 8-cm diameter pots were filled to 4 cm depth with a silt loam soil with a pH of 6.4 and O.M. of 1.8 from Fayetteville, AR. Using the germination data from the POST herbicide assays, samples were sown to achieve approximately 25 plants per pot. Seeds were then covered with approximately 1 cm of soil. Each treatment was replicated twice for a target of 100 plants to germinate in a total of 4 pots. A labeled field rate of clomazone for a silt loam soil of 336 g ai ha^{-1} was applied to three of the four pots. Visual estimates of the percent germination for each sample were recorded from the previous POST-applied herbicide experiments for use in a follow-up PRE herbicide screening experiment. One of the four pots was left untreated to verify that germination ratings previously recorded had not changed while in storage between runs. Seedlings were counted 3 weeks after emergence (WAE) based on a scale from 0 to 100 % ; with 0 being all plants emerged survived the 1x treatment of clomazone and 100 percent with no emerged seedlings. Ratings were done relative to the respective non-treated check of each accession. The same susceptible accession from a commercial source was used as the standard.

Accession evaluations by treatment were classified into four categories: 100- to 71%, 70- to 51%, 50- to 20% and less than 20% control of the accession. This classification will be used to predict the likelihood of resistance evolution in a particular population represented by the accession. An accession was categorized as resistant if the plants controlled by the treatment were less than 70% of the total plants treated.

Baseline Tolerance to Glyphosate, Isoxaflutole and Glufosinate. All accessions were planted and maintained in the greenhouse following the same method described previously. Plants were grown to the 2- to 3-leaf stage, and treated with either glyphosate at 860 g ae ha^{-1}, isoxaflutole at 53 g ai ha^{-1} or glufosinate at 240 g ai ha^{-1}. Glyphosate was applied at the field use rate while isoxaflutole and glufosinate were applied at 0.5x the recommended field use rates. The same susceptible standard was used as in the other resistance bioassays. Following applications, newly emerged plants were removed to evaluate only those that were sprayed with the herbicide. Visual estimates of herbicide efficacy was recorded at 10 days after treatment.

Results and Discussion

Resistance to Rice Herbicides. Of the 82 samples collected in 2010, only 74 had viable seed. The eight samples which did not germinate came from crop consultants; these were immature. The 23 counties from where the accessions were collected represented approximately 652,000 of 722,000 ha or 91% of Arkansas rice hectares in 2010 (Table 1.1).

Resistance to propanil. Of the 74 accessions that germinated, 43 had less than a 100% mortality after treatment with propanil (Table 1.2). The accessions were classified into four categories: susceptible, slightly resistant, moderately resistant, and resistant which were categorized by a range of 100- to 71%, 70- to 51%, 50- to 20% and less than 20% control, respectively. Forty-six accessions were controlled greater than 70% with propanil. Nine accessions were slightly resistant to propanil. Fourteen accessions were considered moderately resistant. The remaining five accessions were highly resistant (Table 1.2). For the majority of samples, the phytotoxicity ratings were similar to the mortality ratings. Accessions 17, 18, 19, and 25 had 44, 43, 63, and 58% mortality, respectively and all survivors did not exhibit any visible injury. Accession 43 had 62% of the plants controlled with propanil, but the accession had only 28% injury rating because the survivors were only slightly injured and recovered from the propanil effect. Likewise, there were accessions that had less mortality, but the survivors showed high injury from propanil. This was observed in populations 9, 10, 11, 33, 34, 35, 38, and 39. Accessions that had surviving plants showed different degrees of injury, indicating different levels of resistance among populations. Resistance to propanil is due to increased detoxification of the herbicide; resistant populations are expected to metabolize propanil at different rates depending on the catabolic activity of arylacylamidase enzyme which detoxifies propanil (Carey et al. 1997). Since the early 1990s, the availability of effective alternative herbicides and implementation of resistance management strategies have reduced the amount of propanil used in Arkansas to only 55% of the total rice hectares in 2006 (Norsworthy et al. 2007a). Of the 29 accessions resistant to propanil, 27 came from counties that historically produce greater than 20,000 ha of rice (FSA 2012). These resistant accessions were collected from counties that represent 399,836 ha or 55.4% of total rice hectares in Arkansas.

Carey et al. (1995) conducted a similar survey in 1992 to determine the extent of propanil-resistant barnyardgrass in Arkansas. At that time, propanil-resistant barnyardgrass had only been confirmed 2 years prior and was a relatively new concept to rice producers. Carey et al. (1995) sampled only accessions which were submitted as suspected propanil-resistant accessions from 19 rice-producing counties, confirming propanil-resistance in 16 of these counties. The present study was conducted to provide a more current ‘snapshot’ random sampling of the majority of rice grown in Arkansas. Since 1990, propanil-resistant *Echinochloa* has spread to at least 16 of the 38 rice producing counties as submitted as potential resistant populations (Carey et al. 1995). This 2010 random survey showed that propanil-resistant barnyardgrass has become a problem in 11 of the 23 counties sampled, despite the alternative chemistries used to manage it. Although the parameters between this study and Carey (et al 1995) were slightly different, the random sampling in this study proves propanil-resistant *Echinochloa* spp continues to be a widespread problem in Arkansas.

<u>Resistance to quinclorac</u>. Quinclorac-resistant *Echinochloa* was the second most common biotype in Arkansas. Thirteen of the 74 accessions, including the susceptible standard, were not controlled (> 70%) by the recommended use rate of quinclorac POST-applied at 564 g ha^{-1} (Figure 2). Norsworthy et al. (2007a) estimated that 7% of the rice in Arkansas was infested with quinclorac-resistant *Echinochloa* in 2006. A mere four years after the previous survey, the survey in 2010 estimated that number to be about 18%. The spread of percent mortality and

phytotoxicity ratings was not as large with quinclorac (Table 1.2). One population to note is number 43. Only 33% of plants in accession 43 survived a quinclorac application and the survivors showed 65% injury three weeks after treatment. This population seems to have a delayed reaction to quinclorac and the possibility of resistance is greater with this accession. The resistant accessions occurred in 11 of the 23 counties sampled. The 11 counties with quinclorac-resistant populations are estimated to infest an equivalent of 348,030 ha or 48.2% of total rice hectares in Arkansas in 2010. Although the occurrence of quinclorac-resistant populations is not as frequent as those of propanil-resistant populations, it is still a major problem in the state's highest rice-producing counties. In fact, 9 of the 13 accessions resistant to quinclorac were also classified as resistant to propanil.

Resistance to clomazone, fenoxaprop, or imazethapyr. *Echinochloa* resistance to imazethapyr or clomazone has been confirmed in Arkansas, but is yet rare in occurrence (Wilson et al. 2010; Norsworthy et al. 2007b). *Echinochloa* has been shown resistant to glyphosate and fenoxaprop-P-ethyl in Australia, California, and Mississippi, USA (Heap 2014; Alarcon-Reverte et al 2013; Thai et al 2012). These herbicides are important in Arkansas rice production and resistance evolution could jeopardize the long-term utility of these herbicides and the US rice industry as a whole. No resistance to clomazone, fenoxaprop, or imazethapyr was observed among the 2010 accessions as the visual control ratings were all 100 phytotoxicity. There were no survivors from the herbicide treatments.

Response to sublethal doses of glufosinate and isoxaflutole. Protecting the utility of herbicides depends greatly on the rotational practices of crops and herbicide modes of action (Bagavathiannan et al. 2015). Glufosinate and isoxaflutole are among the alternative chemistries that can control *Echinochloa* in different crop rotation systems. Upon testing these herbicides at one-half the labeled rate, both treatments controlled all accessions. These herbicides are viable options for *Echinochloa* management outside of rice season. The evolution of glyphosate-resistant barnyardgrass in Australia (Thai et al. 2012) and junglerice in California (Alarcon-Reverte et al. 2013) demonstrates that without being proactive in cropping decisions and diversification of mechanisms of action in Arkansas agriculture, the same consequence will be manifested in the southern US rice belt.

Summary

With a total of 29 resistant accessions across 11 counties, resistance to propanil among *Echinochloa* spp. is the greatest herbicide resistance problem in Arkansas rice production. Quinclorac resistance was detected in 13 accessions also from 11 counties. Of the 13 accessions that were resistant to quinclorac, 9 were also resistant to propanil. *Echinochloa* spp. can be effectively controlled with methods currently available to Arkansas rice growers. All accessions sampled were controlled with a 1x rate of fenoxaprop, clomazone, and imazethapyr. No accessions showed differences in tolerance to a 0.5x rate of glyphosate or isoxaflutole. Glyphosate can still be used for preplant vegetation desiccation or preemergence application in rice. It is reassuring that there were no differences in the response of these accessions to isoxaflutole, which should help preserve future technologies.

Literature Cited

Alarcon-Reverte R, Garcia A, Urzua J, Fischer AJ (2013) Resistance to glyphosate in junglerice (*Echnichloa crus-galli*) from California. Weed Science 61:48-54

Bagavathiannan MV, Norsworthy JK, Scott RC, Barber LT (2013) Answers to frequently asked questions on herbicide resistance management. FSA2172. https://www.uaex.edu/publications/PDF/FSA-2172.pdf . Accessed: March 25, 2015

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2015) Validation of a model to simulate herbicide resistance evolution in barnyardgrass in rice-soybean production system. In: Proceedings of the Weed Science Society of America Annual Meeting, Lexington, KY.

Baltazar AM, Smith Jr RJ (1994) Propanil-resistant barnyardgrass (*Echinochloa crus-galli*) control in rice (*Oryza sativa*). Weed Sci 8:576-581

Carey VF, Hoagland RE, Talbert RE (1995) Verification and distribution of propanil-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas. Weed Technol 9:366-372

Carey VF, Hoagland RE, Talbert RE (1997) Resistance mechanism of propanil-resistant barnyardgrass: II. In-vivo metabolism of the propanil molecule. Pestic Sci 49:333-338

FSA (2012) FSA Crop Acreage Data Reported to the FSA. http://www.fsa.usda.gov/FSA/webapp?area=newsroom&subject=landing&topic=foi-er-fri-cad Accessed July 9, 2012

Hardke JT, Wilson CE (2012) Trends in Arkansas Rice Production. B. R. Wells Research Series 609 Pp. 38-47

Heap I (2014) International survey of herbicide resistant weeds. http://www.weedscience.org. Accessed June 3, 2014

Lovelace ML, Reaper JD, Scherder EF, Schmidt LA, Talbert RE (2000) Multiple resistance of propanil-resistant barnyardgrass (*Echinochloa crus-galli*) to quinclorac. Abstr Proc 28th Rice Tech Work Group 28:153

Lovelace ML, Talbert RE, Hoagland RE, Scherder EF (2003) Investigation of potential quinclorac resistance mechanisms in a multiple-resistant barnyardgrass biotype. Proc South Weed Sci Soc 56:177

Malik MS, Burgos NR, and Talbert RE (2010) Confirmation and control of propanil-resistant and quinclorac-resistant barnyardgrass (*Echinochloa crus-galli*) in rice. Weed Technol 24:226-233

Martinkova ZA, Honek, Lukas J (2006) Seed age and storage conditions influence germination of barnyardgrass (*Echinochloa crus-galli*). Weed Sci 54:298-304

Meier JR, Smith KL, Scott RC, Norsworthy JK (2010) Barnyardgrass (*Echinochloa crus-galli*) control with various herbicide combinations in Clearfield rice (*Oryza sativa*). B. R. Wells Research Series 591 Pp. 154-159

Mitich LW (1990) Barnyardgrass. Weed Technol 4:918-920

Norsworthy JK, Burgos NR, Scott RC, Smith KL (2007a) Consultant perspectives on weed management needs in Arkansas rice. Weed Technol 21:832-839

Norsworthy JK, Scott RC, Smith KL (2007b) Confirmation and management of clomazone-resistant barnyardgrass in rice. Res Ser Ark Agric Exp Stn Bull 560:113–116

Pallett KE, Cramp SM, Little JP, Veerasekaran P, Crudace AJ, Slater AE (2001) Isoxaflutole: the background to its discovery and the basis of its herbicidal properties. Pest Manag Sci 57:133-142

Pellerin KJ, Webster EP (2004) Imazethapyr at different rates and timings in drill- and water-seeded imidazolinone-tolerant rice. Weed Technol 18:223-227

Riar DS, Norsworthy JK, Bond JA, Bararpour MT, Wilson MJ, Scott RC (2012) Resistance of *Echinochloa crus-galli* populations to acetolactate-synthase-inhibiting herbicides. International Journal of Agronomy 2012:1-8

Smith KL, Scott RC, Bond JA, Eubank TE (2009) Glyphosate-resistant Palmer amaranth and ryegrass management. MP479. https://www.uaex.edu/publications/PDF/MP479.pdf. Accessed: March 24th 2015

Smith RJ Jr. (1965) Propanil and mixtures with propanil for weed control in rice. Weeds 13:236-238

Smith RJ Jr. (1968) Weed competition in rice. Weed Sci 16:252-255

Smith RJ Jr. (1974) Competition of barnyardgrass with rice cultivars. Weed Sci 22:423-426

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:234-331

Tan S, Evans RR, Dahmer ML, Sing BK, Shaner DL (2005) Imidazolinone-tolerant crops: history, current status and future. Pest Management Sci 61:246-257

Thai NH, Malone J, Boutsalis P, Preston C (2012) Glyphosate resistance in barnyardgrass (*Echinochloa crus-galli*). http://www.caws.org.au/awc/2012/awc201212371.pdf Accessed: January 24, 2013

Tranel PJ, Wright TR (2002) Resistance of weeds to ALS-inhibiting herbicides: what have we learned? Weed Sci 50:700-712

Wilson MJ, Norsworthy JK, Johnson DB, McCallister EK, Devore JD, Griffith GM, Banagarwa SK, Scott RC, Smith KL (2010) Herbicide programs for controlling ALS-resistant barnyardgrass in Arkansas rice. B. R. Wells Rice Res Ser 581 Pp. 153-157

Yih RY, McRae DH, Wilson HF (1968) Mechanism of selective action of 3’,4’ dichloropropionanilide Plant Physiol 43:1291-1296

Table 1.1. Total number of herbicide-resistant *Echinochloa* spp. accessions by county.

County	Planted rice (ha)[b]	Total samples	Resistant accessions[a] Propanil	Quinclorac	Propanil + quinclorac
Arkansas	50570	3	2	1	1
Ashley	8863	2	0	1	0
Chicot	20666	3	2	1	1
Clay	37950	1	0	0	0
Crittenden	20545	1	0	1	0
Cross	41152	2	1	1	1
Desha	20574	1	0	0	0
Drew	6744	3	0	1	0
Greene	36043	3	0	0	0
Jackson	46068	5	4	1	1
Jefferson	34485	1	0	0	0
Lawrence	49328	7	4	2	2
Lee	14016	1	0	0	0
Lincoln	14246	3	1	1	0
Lonoke	37888	3	1	0	0
Mississippi	21602	4	1	0	0
Monroe	29908	7	7	2	2
Phillips	18957	6	0	0	0
Poinsett	59940	2	2	1	1
Prairie	28468	9	4	0	0
St. Francis	20629	2	0	0	0
White	7147	4	0	0	0
Woodruff	25771	1	0	0	0
Sum	651560	74	29	13	9

[a] An accession was considered resistant if total mortality across all runs was less than 70%.
[b] Represents total hectares planted to rice by county sampled in 2010 totaling 651,560 ha of the 722,190 total ha or 90.2% of total Arkansas rice planted in 2010.

Table 1.2. Mortality and visual phytotoxicity estimates of surviving *Echinochloa* spp. accessions treated with propanil at 4,480 g ai ha^{-1} or quinclorac at 564 g ai ha^{-1} applied to 2- to 3-leaf plants.

			Propanil[c]		Quinclorac[c]	
Accession[a]	County	Germination[b]	Mortality	Phytotoxicity	Mortality	Phytotoxicity
			%			
1	Jefferson	10	100	100	100	100
2	Ashley	5	100	100	100	100
3	Chicot	10	34	40	100	100
4	Lincoln	10	86	85	100	100
5	Monroe	9	62	70	100	100
6	Arkansas	8	100	100	100	100
7	Arkansas	10	39	30	57	60
8	Desha	9	100	100	100	100
9	Arkansas	10	54	90	100	100
10	Monroe	3	22	50	46	53
11	Monroe	8	62	50	79	73
12	Prairie	10	95	99	100	100
13	Monroe	10	27	10	100	100
14	Lee	9	100	100	100	100
15	St. Francis	2	100	100	100	100
16	Lonoke	10	100	100	100	100
17	Prairie	10	44	0	100	100
18	Prairie	10	43	0	100	100
19	Monroe	6	63	0	100	100
20	Cross	10	43	36	25	28
21	Crittenden	10	100	100	59	40
22	Ashley	7	86	93	27	28
23	Chicot	6	100	100	100	100
24	Chicot	10	69	50	48	58
25	Prairie	10	58	0	82	85
26	Lincoln	4	87	100	53	60
27	Lawrence	8	100	100	100	100
28	Lawrence	9	30	27	100	100
29	Lawrence	2	100	100	100	100
30	Lawrence	8	34	31	40	43
31	Lawrence	4	45	42	100	100
32	Lawrence	7	100	100	100	100
33	Monroe	6	13	49	25	25
34	Monroe	9	3	35	100	100
35	Lonoke	10	0	45	100	100
36	Cross	2	100	100	100	100
37	Cross	0	DNG[d]	DNG	DNG	DNG
38	Poinsett	10	0	38	100	100

Table 1.2. Mortality and visual phytotoxicity estimates of surviving *Echinochloa* spp. accessions treated with propanil at 4,480 g ai ha^{-1} or quinclorac at 564 g ai ha^{-1} applied to 2- to 3-leaf plants. (Cont.)

			Propanil[c]		Quinclorac[c]	
Accession[a]	County	Germination[b]	Mortality	Phytotoxicity	Mortality	Phytotoxicity
			%			
39	Mississippi	10	0	35	100	100
40	Mississippi	10	100	100	100	100
41	Mississippi	4	100	100	100	100
42	Mississippi	9	100	100	100	100
43	Lawrence	7	62	28	33	65
44	Clay	0	DNG	DNG	DNG	DNG
45	Lonoke	1	76	66	100	100
46	Jackson	10	70	64	100	100
47	Greene	0	DNG	DNG	DNG	DNG
48	Greene	0	DNG	DNG	DNG	DNG
49	Greene	7	100	100	100	100
50	Greene	10	100	100	100	100
51	Greene	10	81	78	100	100
52	Greene	0	DNG	DNG	DNG	DNG
53	Prairie	10	100	100	100	100
54	Prairie	10	90	97	100	100
55	Prairie	10	95	97	100	100
56	Lincoln	10	38	32	100	100
57	Prairie	8	100	100	100	100
58	Prairie	10	62	64	100	100
59	St. Francis	7	88	87	100	100
60	St. Francis	0	DNG	DNG	DNG	DNG
61	White	8	100	100	100	100
62	White	10	100	99	100	100
63	White	10	100	100	100	100
64	White	5	76	57	100	100
65	Woodruff	6	98	58	100	100
66	White	0	DNG	DNG	DNG	DNG
67	Phillips	9	100	100	100	100
68	Phillips	7	100	100	100	100
69	Phillips	5	100	100	100	100
70	Phillips	10	98	98	100	100
71	Phillips	10	80	98	75	78
72	Clay	10	100	100	100	100
73	Phillips	10	100	100	100	100
74	Drew	10	100	86	13	15
75	Drew	10	100	100	100	100
76	Drew	10	100	100	100	100
77	Poinsett	10	34	48	23	30
78	Poinsett	0	DNG	DNG	DNG	DNG

Table 1.2. Mortality and visual phytotoxicity estimates of surviving *Echinochloa* spp. accessions treated with propanil at 4,480 g ai ha^{-1} or quinclorac at 564 g ai ha^{-1} applied to 2- to 3-leaf plants. (Cont.)

			Propanil[c]		Quinclorac[c]	
Accession[a]	County	Germination[b]	Mortality	Phytotoxicity	Mortality	Phytotoxicity
			%			
79	Jackson	9	81	39	100	100
80	Jackson	10	66	36	31	30
81	Jackson	8	41	27	100	100
82	Jackson	7	41	19	100	100

[a] Numbers represent the coding system used for accession identification.

[b] Germination ratings were collected 7-10 days after planting on a scale of 0-10 whereas 0 was no plants germinated and 10 was excellent germination. Following germination ratings, plants were thinned to 25 per plot.

[c] Injury was rated 10 and 21 days after treatment for propanil and quinclorac treatments, respectively.

[d] Abbreviation: DNG, did not germinate

Figure 1.1. Distribution of *Echinochloa* spp. accessions from Arkansas rice-producing counties in 2010 showing less than 70 percent mortality with propanil treatment at 4,480 g ai ha^{-1}.

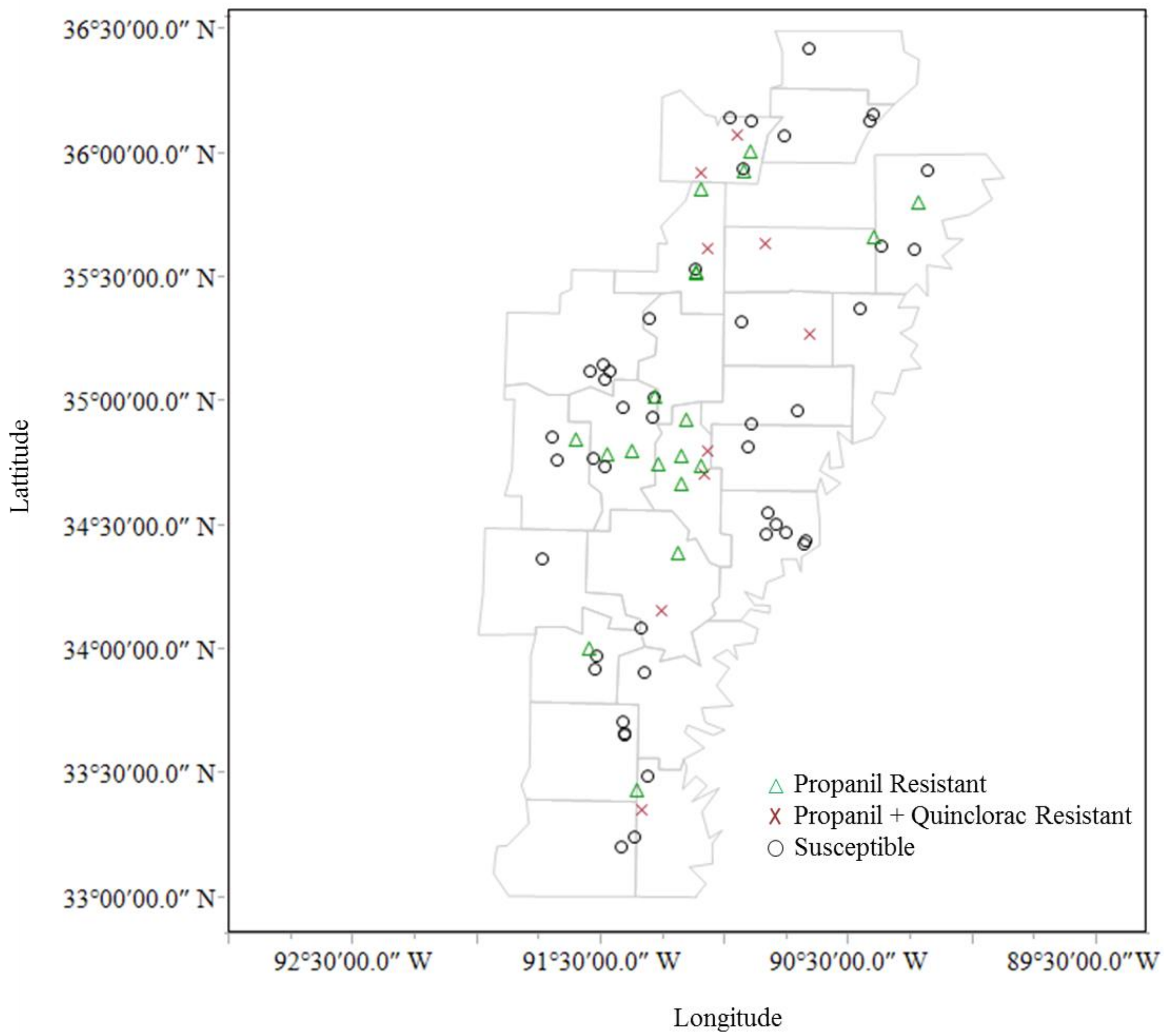
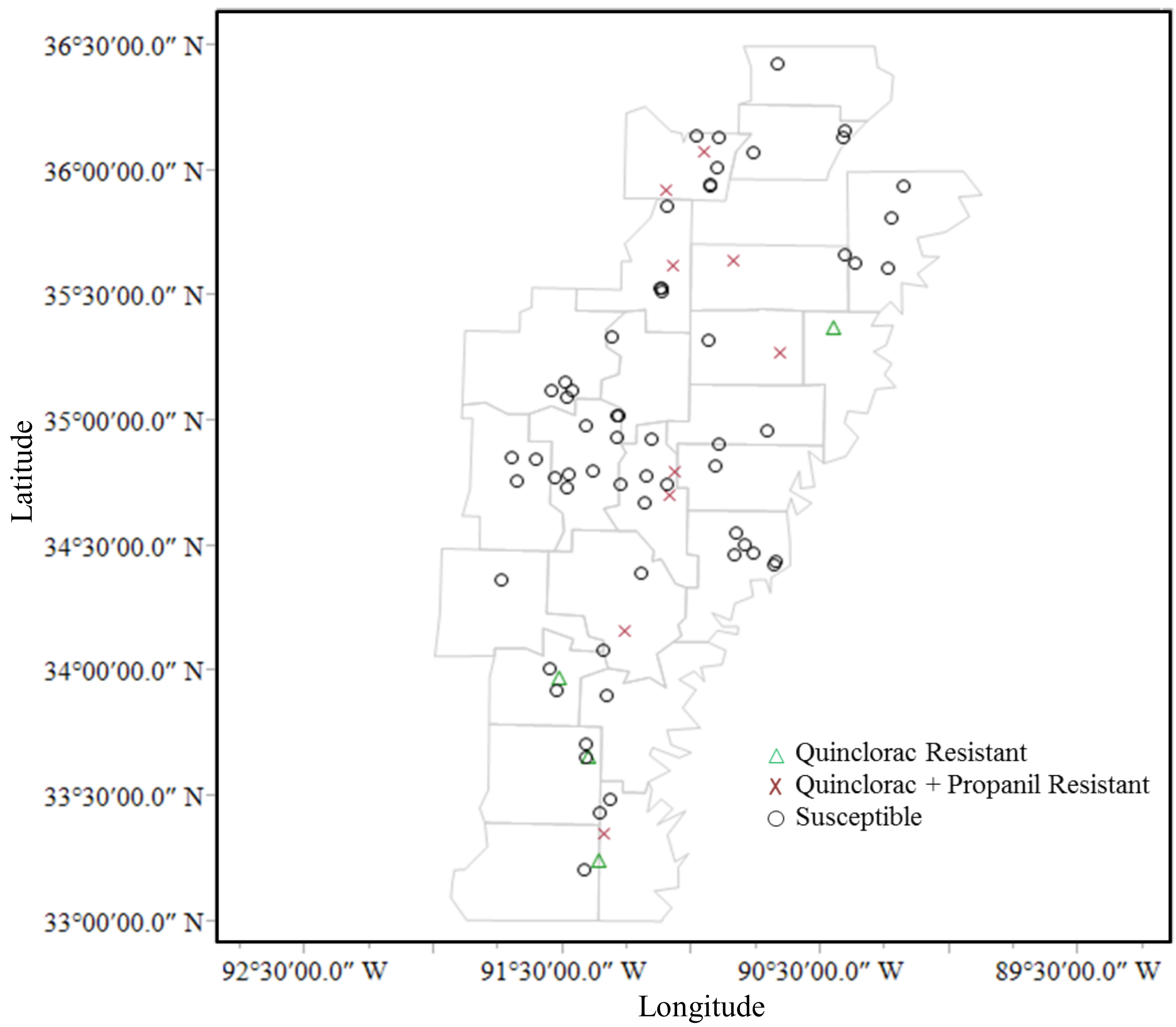


Figure 1.2. Distribution of *Echinochloa* spp. accessions, from Arkansas rice-producing counties in 2010 showing less than 70 percent control from quinclorac at 564 g ai ha^{-1}.



.

Appendices

Appendix 1.1. *Echinochloa* spp. accessions collected in 2010 and their respective county and GPS coordinates within Arkansas.

Accession[a]	County	Latitude	Longitude
1	Jefferson	34°21′46″ N	91°55′25.26″ W
2	Ashley	33°12′18″ N	91°31′24.66″ W
3	Chicot	33°26′01″ N	91°27′10.62″ W
4	Lincoln	33°55′20″ N	91°39′39.84″ W
5	Monroe	34°40′14″ N	91°14′58.32″ W
6	Arkansas	34°05′09″ N	91°26′24.24″ W
7	Arkansas	34°09′39″ N	91°20′40.2″ W
8	Desha	33°54′14″ N	91°25′10.74″ W
9	Arkansas	34°23′29″ N	91°15′47.82″ W
10	Monroe	34°42′32″ N	91°08′05.04″ W
11	Monroe	34°44′52″ N	91°21′42.78″ W
12	Prairie	34°58′40″ N	91°31′57.06″ W
13	Monroe	34°55′39″ N	91°13′14.22″ W
14	Lee	34°49′02″ N	90°54′54″ W
15	St. Francis	34°54′24″ N	90°53′54.84″ W
16	Lonoke	34°45′44″ N	91°51′12.3″ W
17	Prairie	34°48′06″ N	91°29′28.08″ W
18	Prairie	34°47′19″ N	91°36′36″ W
19	Monroe	34°44′42″ N	91°08′49.08″ W
20	Cross	35°16′19″ N	90°36′56.88″ W
21	Crittenden	35°22′34″ N	90°21′33.84″ W
22	Ashley	33°14′42″ N	91°27′46.44″ W
23	Chicot	33°29′26″ N	91°24′12.72″ W
24	Chicot	33°21′21″ N	91°26′04.74″ W
25	Prairie	N/A[b]	N/A
26	Lincoln	33°58′36″ N	91°38′59.7″ W
27	Lawrence	36°08′27″ N	91°00′20.34″ W
28	Lawrence	35°56′01″ N	90°56′23.1″ W
29	Lawrence	35°56′28″ N	90°56′33.84″ W
30	Lawrence	36°04′31″ N	90°58′38.7″ W
31	Lawrence	36°00′48″ N	90°54′18.48″ W
32	Lawrence	36°07′48″ N	90°54′10.68″ W
33	Monroe	34°48′04″ N	91°06′49.38″ W
34	Monroe	34°46′49″ N	91°14′39.9″ W
35	Lonoke	34°50′56″ N	91°45′59.28″ W
36	Cross	35°19′24″ N	90°56′53.28″ W
37	Cross	35°13′27″ N	90°48′42.48″ W
38	Poinsett	35°39′50″ N	90°17′39.66″ W
39	Mississippi	35°48′26″ N	90°04′20.82″ W
40	Mississippi	35°36′41″ N	90°05′21.72″ W
41	Mississippi	35°37′37″ N	90°15′00.9″ W
42	Mississippi	35°56′04″ N	90°01′06.66″ W
43	Lawrence	35°55′28″ N	91°09′20.76″ W

Appendix 1.1. *Echinochloa* spp. accessions collected in 2010 and their respective county and GPS coordinates within Arkansas. (Cont.)

Accession[a]	County	Latitude	Longitude
44	Clay	36°23′39″ N	90°23′23.22″ W
45	Lonoke	34°51′14″ N	91°52′30.48″ W
46	Jackson	35°51′33″ N	91°08′59.4″ W
47	Greene	35°59′39″ N	90°28′23.7″ W
48	Greene	35°59′14″ N	90°29′38.52″ W
49	Greene	36°09′26″ N	90°17′34.14″ W
50	Greene	36°07′53″ N	90°18′22.98″ W
51	Greene	36°04′09″ N	90°44′03.18″ W
52	Greene	36°03′16″ N	90°45′37.38″ W
53	Prairie	34°55′59″ N	91°22′53.76″ W
54	Prairie	34°46′14″ N	91°40′33.6″ W
55	Prairie	35°01′01″ N	91°22′26.46″ W
56	Lincoln	34°00′25″ N	91°41′28.32″ W
57	Prairie	34°44′04″ N	91°37′07.26″ W
58	Prairie	35°01′23″ N	91°22′53.76″ W
59	St. Francis	34°57′39″ N	90°40′21.42″ W
60	St. Francis	34°58′54″ N	90°48′37.2″ W
61	White	35°07′23″ N	91°41′40.56″ W
62	White	35°09′02″ N	91°37′55.14″ W
63	White	35°07′16″ N	91°35′47.58″ W
64	White	35°05′29″ N	91°37′10.56″ W
65	Woodruff	35°19′54″ N	91°24′24.9″ W
66	White	35°22′02″ N	91°28′33.12″ W
67	Phillips	34°32′59″ N	90°49′18.36″ W
68	Phillips	34°26′09″ N	90°37′50.58″ W
69	Phillips	34°30′08″ N	90°46′30.6″ W
70	Phillips	34°28′04″ N	90°49′34.32″ W
71	Phillips	34°25′32″ N	90°38′22.8″ W
72	Clay	36°25′34″ N	90°36′50.28″ W
73	Phillips	34°28′26″ N	90°43′59.94″ W
74	Drew	33°39′53″ N	91°30′41.28″ W
75	Drew	33°39′17″ N	91°30′57.54″ W
76	Drew	33°42′36″ N	91°31′16.62″ W
77	Poinsett	35°38′33″ N	90°49′58.5″ W
78	Poinsett	35°32′49″ N	91°00′22.68″ W
79	Jackson	35°31′49″ N	91°10′24.06″ W
80	Jackson	35°37′21″ N	91°07′09.3″ W
81	Jackson	35°31′05″ N	91°10′28.62″ W
82	Jackson	35°31′44″ N	91°10′34.92″ W

[a] GPS coordinates and county of orgin of all accessions including the 8 accessions that did not germinate.

[b] Sample from Prairie County extension agent without GPS coordinates.

Appendix 1.2. Survival of *Echinochloa* spp. plants at 1 week after treatment with propanil at 4,480 g ai ha^{-1} from accessions obtained from rice fields in counties in Arkansas in 2010.[a b]

Accession	County	Propanil	
		Treated	Survivors
		#	
3	Chicot	124	42
4	Lincoln	122	105
5	Monroe	113	70
7	Arkansas	131	51
9	Arkansas	87	47
10	Monroe	68	15
11	Monroe	113	70
12	Prairie	21	20
13	Monroe	116	31
17	Prairie	93	41
18	Prairie	102	44
19	Monroe	101	64
20	Cross	83	36
22	Ashley	37	32
24	Chicot	137	95
25	Prairie	116	67
26	Lincoln	23	20
28	Lawrence	126	38
30	Lawrence	124	42
31	Lawrence	99	45
33	Monroe	116	15
34	Monroe	97	3
43	Lawrence	145	90
45	Lonoke	142	108
46	Jackson	119	83
51	Greene	101	82
54	Prairie	30	27
55	Prairie	40	38
56	Lincoln	111	42
58	Prairie	76	47
59	St. Francis	69	61
62	White	18	17
64	White	96	73
65	Woodruff	119	117
70	Phillips	96	94
71	Phillips	25	20
74	Drew	56	46
77	Poinsett	140	47
79	Jackson	101	82
80	Jackson	111	73
81	Jackson	103	42

Appendix 1.2. Survival of *Echinochloa* spp. plants at 1 week after treatment with propanil at 4,480 g ai ha^{-1} from accessions obtained from rice fields in counties in Arkansas in 2010.[a b](Cont.)

Accession	County	Propanil	
		Treated	Survivors
		#	
82	Jackson	100	41

[a] Counts were totaled from the two reps of 50 plants each for a target of approximately 100 plants of accessions that were not controlled 100 percent.

[b] Accessions that were completely controlled (100% mortality) were omitted from this analysis.

Appendix 1.3. Survival of *Echinochloa* spp. plants, 3 weeks after treatment with quinclorac at 564 g ai ha^{-1} in Arkansas in 2010.

Accession	County	Quinclorac	
		Treated	Resistant
		#	
7	Arkansas	94	54
10	Monroe	70	32
11	Monroe	99	78
20	Cross	89	22
21	Crittenden	91	54
22	Ashley	85	23
24	Chicot	103	49
25	Prairie	106	87
26	Lincoln	75	40
30	Lawrence	103	41
33	Monroe	76	19
43	Lawrence	101	33
71	Phillips	97	73
74	Drew	70	9
77	Poinsett	100	23
80	Jackson	81	25

[a] Counts were totaled from the two reps of 50 plants each for a target of approximately 100 plants of accessions that were not controlled 100 percent.
[b] Accessions that were completely controlled (100% mortality) were omitted from this analysis.

Appendix 1.4. Sources of materials.

Herbicide	Trade name	Formulation	Rate	Manufacturer	Address	Website
		g ai L^{-1}	g ai ha^{-1}			
Glyphosate	Roundup WeatherMax	540	580[a]	Monsanto Company	St. Louis, MO	http://www.monsanto.com/
Imazethapyr	Newpath	240	105	BASF Company	Research Triangle Park, NC	http://www.basf.com
Isoxaflutole	Balance Flexx	240	88	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Propanil	Stam	480	4,480	Dow AgroScience	Indianapolis, IN	http://www.dowagro.com/
Fenoxaprop	Ricestar HT	70	86	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Quinclorac	Facet	750[b]	564	BASF Company	Research Triangle Park, NC	http://www.basf.com
Clomazone	Command	360	336	Helena Chemical Co.	Collierville, TN	http://www.helenachemical.com
Glufosinate	Ignite	281	240	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Crop oil concentrate	Agridex		1 % v/v	Helena Chemical Co.	Collierville, TN	http://www.helenachemical.com
Non-ionic surfactant	Induce		0.25 % v/v	Helena Chemical Co.	Collierville, TN	http://www.helenachemical.com

[a] Glyphosate rate is reported as g ae ha^{-1}

[b] Quinclorac formulation is reported as g ai kg^{-1}

Chapter 2

Use of HPPD-inhibiting Herbicides for Control of Troublesome Weeds in Arkansas

Abstract

Transgenic crops provide cotton and soybean producers additional weed control options for many of the most problematic weeds in Arkansas production systems. The expected commercialization of 4-hydroxyphenylpyruvate dioxygenase (HPPD)-resistant soybean in 2017 and cotton in 2020 will provide producers the option to apply HPPD-inhibiting herbicides that will offer an alternative mechanism of action for previously hard-to-control weeds. Experiments were conducted in 2010 and 2011 to determine the efficacy of HPPD-inhibiting herbicides applied preemergence (PRE) or postemergence (POST) for control of problematic weeds of cotton and soybean in Arkansas. PRE experiments were conducted to understand the length and degree of control of Palmer amaranth and barnyardgrass that could be expected with HPPD-inhibiting herbicides compared with current standards on silt loam and clay soil textures. The HPPD herbicides evaluated included mesotrione, tembotrione, and isoxaflutole compared to several standards currently labeled in soybean. In the POST experiment, applications of isoxaflutole, tembotrione, glyphosate, and two rates of glufosinate applied alone and both HPPD herbicides combined with glyphosate or glufosinate were evaluated for control of Palmer amaranth, barnyardgrass, hemp sesbania, and yellow nutsedge. When herbicides were applied PRE, the HPPD-inhibiting herbicides and the current standard treatments all provided greater than 90% control of Palmer amaranth 4 WAT on both soil textures. Barnyardgrass control with HPPD-inhibitors was generally weaker than the current standards with the exception of mesotrione which proved to be comparable to the standards 4 WAT. In the POST experiment, all treatments, except for glyphosate alone, provided excellent (>85%) control of Palmer amaranth less than 10 cm in height. Barnyardgrass, yellow nutsedge, and hemp sesbania were effectively controlled with HPPD-inhibiting herbicides with and without glufosinate or glyphosate.

Nomenclature: Flumioxazin; fomesafen; glufosinate; glyphosate; isoxaflutole; mesotrione; pendimethalin; *S*-metolachlor; tembotrione; thiencarbazone plus isoxaflutole; sulfentrazone plus metribuzin; *S*-metolachlor plus metribuzin; *S*-metolachlor plus fomesafen; *S*-metolachlor plus mesotrione; chlorimuron plus flumioxazin plus thifensulfuron; barnyardgrass, *Echinochloa crus*-galli (L.) Beauv.; hemp sesbania *Sesbania herbaceae* (P. Mil.) McVaugh; Palmer amaranth, *Amaranthus palmeri* (L.) S. Wats.; yellow nutsedge, *Cyperus esculentus*; cotton, *Gossypium hirsutum* L.; soybean, *Glycine max* (L.) Merr.

Key words: HPPD-inhibiting herbicides, preemergence, postemergence, tank-mix, genetically modified crops.

Introduction

Options for weed control in Arkansas crops were broadened with the introduction of transgenic crops, specifically glyphosate-resistant soybean and cotton in 1996 and 1997, respectively. The adoption of glyphosate-resistant crops came with a dramatic shift in herbicide use patterns, most notably the almost sole reliance on glyphosate (Young 2006). Glyphosate is a non-selective herbicide that inhibits the 5-enolpyruvylshikimate-3-photsphate synthase (EPSPS) within a plant. Producers were allowed to apply up to 3.3 kg ae ha^{-1} yr^{-1} over multiple application timings (Anonymous 2011). Due to the fact that glyphosate applications are cheap, effective, and simple (Duke and Powles 2009), applications were being made multiple times per year in cotton and soybean and thus replaced tank mixtures of herbicides, tillage, and residual herbicides in the late 1990s and early 2000s (Beckie 2006; Dill et al. 2008; Young 2006). Extensive and often exclusive use of glyphosate created an increasing number of glyphosate-resistant weeds (Heap 2014). In order to mitigate weed resistance to glyphosate, new mechanisms of action are being sought that can be integrated into current or future cropping systems. In a survey conducted by Norsworthy et al. (2007) in Arkansas, cotton consultants overwhelmingly expressed the importance of a need for new tools for resistant weed management.

Another transgenic option for producers to apply an effective broad-spectrum herbicide in crop was the release of glufosinate-resistant crops. Glufosinate-resistant crops were being developed almost concurrently with their glyphosate-resistant crop counterparts. Glufosinate has a different mechanism of action than glyphosate. Glufosinate is an inhibitor of the glutamine synthetase (Mallory-Smith and Retzinger 2003).

Although glufosinate-resistant cotton is grown in the U.S., glyphosate-resistant cotton comprises the overwhelming majority of herbicide-resistant cotton grown. Herbicide-resistant cotton increased from 46% of the acreage in 2000 to 80% in 2012 (USDA-ERS 2012). In Arkansas, Palmer amaranth resistance to acetolactate synthase (ALS)-inhibiting herbicides and glyphosate were documented in 1994 and 2006, respectively (Heap 2014). When Palmer amaranth is resistant to both ALS-inhibitors and glyphosate, there is often no effective over-the-top herbicide option in glyphosate-resistant cotton. The advent of effective control options will help alleviate the detrimental impact of herbicide-resistant Palmer amaranth in cotton and soybean.

In 2016 and 2020, soybean and cotton are expected to be released that are resistant to a mechanism of action currently used in corn (*Zea mays* L.) and grain sorghum (*Sorghum bicolor* L.) production, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides. HPPD-inhibiting herbicides prevent the formation of homogentisate in the formation of chloroplasts and carotenoids (Grossman and Ehrhardt 2007; Viviani et al. 1998). Enzymatic inhibition results in a bleaching effect in plants due to the absence of carotenoid biosynthesis (Pallett et al. 2001). HPPD-inhibiting herbicides are known to be broad spectrum, often controlling both grass and broadleaf species. This technology will provide soybean and cotton producers with another option for control of troublesome weeds. These HPPD-resistant crops will eventually possess resistance to glyphosate and glufosinate (Stuebler et al. 2008). The combination of these traits will provide producers additional options to combat the resistant weeds currently infesting cotton and soybean fields.

In a survey of Arkansas cotton consultants in 2011, of the most problematic weeds in cotton, Palmer amaranth, hemp sesbania, yellow nutsedge, and barnyardgrass were ranked among the top 10 (Riar et al. 2013). Palmer amaranth has evolved wide-spread resistance to glyphosate and ALS-inhibiting herbicides making POST over-the-top control impossible in glyphosate-resistant cotton (Sosnoskie et al. 2009). Applications of glyphosate to control troublesome weeds, such as hemp sesbania and yellow nutsedge, have been marginal depending on rate and size of the plant at application (Jordan et al. 1997; Nelson et al. 2002). Applications of glufosinate on both hemp sesbania and yellow nutsedge have proven very effective (Corbett et al. 2004; Nelson et al. 2002).

Barnyardgrass is a problematic weed due to its ability to germinate and grow under a wide variety of conditions (Keeley and Thullen 1991). It has been predicted that barnyardgrass will eventually evolve resistance to glyphosate (Bagavathiannan et al. 2011). The addition of HPPD-resistant cotton and soybean could be an additional tool that can be used to combat weed resistance. The weed spectrum shift caused by glyphosate-resistant crops has affected the entire southern U.S. where cotton and soybean are two of the principle crops (Webster and Nichols 2012). The objectives of this research were to navigate alternative options in the use of HPPD-inhibiting herbicides for crops which until 2016 were not able to withstand an application of such herbicide. This research also aims to explore the most efficient method of application to control four of the most troublesome weeds in Arkansas: Palmer amaranth, barnyardgrass, hemp sesbania, and yellow nutsedge.

Materials and Methods

Length and Degree of Control with PRE-applied HPPD-inhibiting Herbicides Compared to Current Herbicide Standards. Experiments were conducted during the summers of 2010 and 2011 to determine the length of residual control with HPPD-inhibiting herbicides compared to the current PRE-applied herbicides commonly used in Arkansas soybean production systems.

Experiments were conducted at the University of Arkansas Northeast Research and Extension Center (NEREC) in Keiser, AR in 2010 on a Sharkey (very fine, smectitic, thermic Chromic Epiaquerts, pH 6.5, OM 3.8%) and 2011 on a Sharkey-Steele (very fine, smectitic, thermic Chromic Epiaquerts, pH 6.7, OM 3.3%). Experiments were also conducted at the University of Arkansas Agricultural Research and Extension Center (AAREC) in Fayetteville, AR in 2010 on a Captina silt loam (fine-silty, siliceous, active, mesic, Typic Fragiudults, pH 6.4, OM 1.8%), in 2011 on a Johnsburg silt loam (fine-silty, mixed active, mesic, Aquic Fragiudults, pH 6.5, OM 1.4%), and in 2011 at the University of Arkansas PineTree Branch Experiment Station (PTBES) near Colt, AR on a Calloway silt loam (fine-silty, mixed active thermic Aquic Fraglossudalfs, pH 6.5, OM 2.2%). Soil samples from the top 10 cm were analyzed from all locations to determine soil properties on all five experimental sites (Table 2.1). Soil organic matter (OM) was determined using loss on ignition (Dean 1974).

Experiments conducted in 2010 and 2011 at the AAREC and in 2010 at the NEREC were under an overhead irrigation system, and in 2011 at NEREC and PTBES, the experiment was surface irrigated. Surface irrigation involved building a levee around the field and applying enough water inside the levee to saturate the soil in the experimental site to activate treatments and germinate weed seeds. The experimental design was a randomized complete block with four replications with the soil texture being the fixed variable (clay, silt loam) and treatments were random. The experimental plots were 1 m wide by 2 m long separated by 2 m alleys between the plots and four replications at all locations. The front 1 by 1 m of each plot was sown with 3,000 barnyardgrass seeds and the remaining 1 by 1 m square was sown with approximately 5,000 Palmer amaranth seeds prior to applying the herbicides. All seeds were lightly incorporated with a rake to approximately a 1.5-cm depth. Barnyardgrass seed was obtained from Azlin Seed

Service (Leland, MS 38756), and Palmer amaranth seed was collected from an infested field at AAREC the previous fall. Herbicide treatments for the silt loam locations were isoxaflutole at 88 g ai ha^{-1}, tembotrione at 92 g ai ha^{-1}, thiencarbazone-methyl + isoxaflutole at 37 and 92 g ai ha^{-1}, respectively, mesotrione at 210 g ai ha^{-1}, *S*-metolachlor at 1335 g ai ha^{-1}, pendimethalin at 1119 g ai ha^{-1}, fomesafen at 280 g ai ha^{-1}, sulfentrazone + metribuzin at 151 and 227 g ai ha^{-1}, respectively, *S*-metolachlor and metribuzin at 1545 and 368 g ai ha^{-1}, respectively, *S*-metolachlor and fomesafen at 1217 and 266 g ai ha^{-1}, respectively, flumioxazin at 71 g ai ha^{-1}, *S*-metolachlor and mesotrione at 1873 and 185 g ai ha^{-1}, respectively, and chlorimuron ethyl + flumioxazin + thifensulfuron methyl at 23 + 72 + 7 g ai ha^{-1}, respectively. Herbicide treatments for the Keiser location were isoxaflutole at 105 g ai ha^{-1}, tembotrione at 92 g ai ha^{-1},thiencarbazone-methyl + isoxaflutole at 37 and 92 g ai ha^{-1}, respectively, mesotrione at 210 g ai ha^{-1}, *S*-metolachlor at 1784 g ai ha^{-1}, pendimethalin at 1704 g ai ha^{-1}, fomesafen at 280 g ai ha^{-1}, sulfentrazone + metribuzin at 202 and 303 g ai ha^{-1}, respectively, *S*-metolachlor and metribuzin at 1987 and 473 g ai ha^{-1}, respectively, *S*-metolachlor and fomesafen at 1217 and 266 g ai ha^{-1}, respectively, flumioxazin at 71 g ai ha^{-1}, *S*-metolachlor and mesotrione at 1873 and 185 g ai ha^{-1},respectively, and chlorimuron ethyl + flumioxazin + thiefensulfuron methyl at 23 + 72 + 7 g ai ha^{-1}, respectively. Phytotoxicity was visually rated on a scale of 0 to 100%, with 0 being no plant injury and 100 complete control. Weed control in plots was rated weekly for 8 to 10 weeks after application, which is the length of time generally needed for soybean and cotton to achieve a dense crop canopy (Holt and Orcutt 1991; Jha and Norsworthy 2009; Reddy and Boykin 2010). Barnyardgrass and Palmer amaranth seedlings m^{-2} were counted in 2010 and 2011. All Palmer amaranth and barnyardgrass counts were reported as a percent of the total relative to the nontreated control to compensate for variation differences in germination from seed sources between years. Percent control data for barnyardgrass did not vary across soil textures; therefore, the means were averaged and ran as ANOVA using Fisher's t-test using JMP V. 9.0.0.

POST HPPD-inhibiting Herbicides Applied Alone and in Combinations with Glufosinate or Glyphosate. Field studies were conducted in 2010 and 2011 at the AAREC. For both years, the experimental area was tilled, bedded, and then the beds were knocked down to a 30.5 cm wide surface using a bed conditioner. The row width of the implements used at the AAREC was changed in the winter of 2010; therefore, the summer of 2010 row centers were 0.98 m apart and in 2011 row centers were 0.91 m. The experiment was conducted as a randomized complete block with factorial treatment structure arrangement of 4 POST herbicide timings and 11 herbicide treatments with four replications both years. Plot dimensions were 30.5 cm by 3.5 m with a non-planted row separating the plots and a 1 m alley between replications. In 2010, the beds were hand-sown to glyphosate-resistant (GR) Palmer amaranth, GR johnsongrass, hemp sesbania, and barnyardgrass. Each plant species were sown in two 1 m length rows on the left and right side of the bed separated by 15 cm to minimize competition among weeds. Glyphosate-susceptible (GS) Palmer amaranth, hemp sesbania, and barnyardgrass were planted in the same manner in 2011 as in 2010. The GR johnsongrass did not germinate in 2010 and therefore was not included in the 2011 planting. GS Palmer amaranth was used in 2011 due to lack of sufficient GR seed for this experiment. The hemp sesbania and barnyardgrass seed that was sown both years was purchased from Azlin Seed Service and was not resistant to any herbicide used in this experiment based on a previous resistance screen. The GR Palmer amaranth used in 2010 was collected from a known GR accession at the AAREC in Washington County, AR. A natural population of yellow nutsedge was present both years. Plots were planted in fields with access to overhead irrigation to provide adequate moisture for weed seed germination both years.

All herbicides were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with Teejet 110015XR flat-fan nozzles (TeeJet XR110015 flat-fan nozzle, Spraying Systems Co., Wheaton, IL 60189) spaced 48 cm apart at a pressure of 276 kPa. Herbicide rates were chosen based on recommendations in the Arkansas 2010 Weed and Brush Control MP-44 (Scott et al. 2011). Application timings were based on size of the fastest growing weed in the plot, which was Palmer amaranth. Both years the applications were applied between the hours of 10:00 AM and 4:00 PM based on work done by Sellers et al. (2003) that determined that between 4 hours following sunrise to 4 hours prior to sunset is optimum time for application of glufosinate. In 2010, Palmer amaranth sizes were 2.5- to 7.5-, 25- to 38-, and 38- to 50-cm tall at application. In 2011, Palmer amaranth size at application was 2.5 to 10-, 30- to 45-, and 45- to 65-cm. Yellow nutsedge, hemp sesbania, and barnyardgrass were all 2.5 to 7.5 cm for both years at the first application timing. The herbicide treatments were set as the fixed variable within a site year since weed size at application slightly varied between years.

Treatments applied for both years were isoxaflutole plus a methylated seed oil (MSO) at 105 g ai ha^{-1} + 1% v/v, respectively, tembotrione plus a MSO at 92 g ai ha^{-1} + 1% v/v, respectively, two rates of glufosinate (450 and 595 g ai ha^{-1}), and glyphosate at 860 g ae ha^{-1}. Isoxaflutole and tembotrione were also applied with both rates of glufosinate and the single rate of glyphosate for a total of 11 herbicide treatments. Additionally, a nontreated control was included to allow weed control to be visually assessed on a 0 to 100% scale, with 0 representing no control and 100 being plant death. Weed control was evaluated 3 weeks after each application. The timing of application across years differed slightly; therefore, data were analyzed separately by year. Fisher's protected LSD was used to separate means across herbicide treatments and timings.

Results and Discussion

Length and Degree of Control with PRE-applied HPPD-inhibiting Herbicides Compared to Current Herbicide Standards. Although herbicide rates were adjusted for soil texture their efficacy differed by soil texture. This could be a function of irrigation or biotype differences among experimental sites; thus, weed control and weed density data are presented by soil texture. The effect of year and location and their interaction with herbicide was nonsignificant for Palmer amaranth and barnyardgrass control for the silt-loam soil; thus, the control data were pooled over years and locations. Control for both Palmer amaranth and barnyardgrass on the clay soil differed by year; therefore, means were separated by year.

Under overhead irrigation, thiencarbazone + isoxaflutole and *S*-metolachlor + mesotrione controlled Palmer amaranth equal to all non HPPD-containing treatments at 8 WAT (Table 2.2). In 2010, tembotrione, mesotrione, and isoxaflutole provided 82, 80, and 75% control, respectively; however, all were well below the industry standards, which provided ≥90% control on the clay soil 8 WAT (0.62 g g^{-1} clay). When surface irrigation was used to activate the herbicides in 2011 at Keiser, control for all treatments 4 WAT were greater than 90%. At 8 WAT, control differed considerably by treatment; mesotrione, *S*-metolachlor + mesotrione, thiencarbazone + isoxaflutole, and isoxaflutole were all comparable to the industry standards. Tembotrione alone was the only HPPD-inhibiting herbicide that did not provide control of Palmer amaranth comparable to the industry standards. The combination of *S*-metolachlor + mesotrione provided 91% control or above for both years. The high control is likely from the *S*-

metolachlor portion of the combination since when applied alone *S*-metolachlor provided at least 90% control both years.

All treatments were able to provide at least 4 weeks of > 90% control of Palmer amaranth on the silt loam soil at Fayetteville and PineTree (Table 2.3). Palmer amaranth control with the HPPD-inhibiting herbicides isoxaflutole and mesotrione were comparable to the non-HPPD-inhibiting herbicides at 10 WAT on the silt loam soil. When mesotrione was applied with *S*-metolachlor, effective Palmer amaranth control (>90%) was obtained through 10 WAT. Tembotrione alone did not provide comparable Palmer amaranth control to the industry standards at 10 WAT. The addition of thiencarbazone to isoxaflutole did not increase control or length of control of Palmer amaranth likely because the population of Palmer amaranth evaluated in this experiment is resistant to ALS-inhibiting herbicides. When end-of-season counts were conducted, the Palmer amaranth densities differed tremendously among treatments (Table 2.4). This is to be expected as there was no crop competition to provide a canopy to assist the herbicides in preventing late-season emergence. The fact that some treatments provided a high level of control through 10 WAT is evidence that season-long control may occur in some instances when some of the herbicides evaluated here are used in HPPD-resistant soybean or cotton.

Isoxaflutole and tembotrione did not provide adequate residual control of barnyardgrass through 4 WAT when applied alone (Table 2.5). Barnyardgrass control with mesotrione, isoxaflutole, and tembotrione on the clay soil ranged from 53 to 75% in 2010 at 4 WAT. Mesotrione was among the herbicide treatments supplying the highest level of barnyardgrass control at 4 WAT in 2010 and at 4 and 8 WAT in 2011.

Barnyardgrass on a silt loam soil treated with thiencarbazone + isoxaflutole and *S*-metolachlor + mesotrione resulted in greater than 90% control 2 WAT and residual control continued to remain high through 10 WAT (Table 2.6). The extended control may have been partially a result of control provided by the ALS-inhibitor thiencarbazone and the chloroacetamide *S*-metolachlor that are marketed as a premix with these HPPD herbicides. Barnyardgrass control with the HPPD-inhibiting herbicides alone ranged from 13 to 53% at 10 WAT, which was markedly less than the level of control obtained with many of the industry standards.

There was a tremendous amount of variability in the barnyardgrass counts among plots on both soil textures, resulting in less detectable differences among herbicide treatments than observed with control data (Table 2.7). Late season barnyardgrass densities in plots treated with HPPD-inhibiting herbicides alone did not differ from the nontreated control, and barnyardgrass densities in HPPD-treated plots alone were often greater than those in plots treated with the herbicides currently labeled for use in soybean. Hence, it is likely that some of the herbicides that are currently being used in soybean today will continue to be needed once HPPD-resistant soybean or cotton is commercialized.

POST HPPD-inhibiting Herbicides Applied Alone and in Combinations with Glufosinate or Glyphosate. In 2010, the seed sourced for the glyphosate-resistant johnsongrass failed to germinate and no data were collected. After multiple attempts to alleviate dormancy, GR johnsongrass was not included in the 2011 trial. The accession of Palmer amaranth used in 2010 was different than that used in 2011. While both were expected to have resistance, the 2011 accession was, in fact, susceptible to glyphosate at 860 g ha^{-1}, which was later confirmed in a greenhouse trial (data not shown). When plants began to emerge, Palmer amaranth quickly overtook most of the natural weed population and other planted weeds. Following trial establishment, it was soon apparent that in addition to the Palmer amaranth that was planted in the 1-m rows, both fields had an abundance of a natural Palmer amaranth population. It has been well documented that *Amaranthus* has a very prolific growth habit, especially Palmer amaranth (Horak and Loughin 2000; Keeley et al. 1987). The excess Palmer amaranth in the field soon outgrew the other planted weed species, eventually shading them. Hence, the first application at the smallest weed size timing was the only application that provided effective spray coverage to all four of the planted weed species.

Palmer Amaranth Control. Palmer amaranth control differed by weed size each year; therefore, data are presented separately by year. Within each year, there was a herbicide treatment by timing interaction for Palmer amaranth. In 2010, glyphosate at 860 g ae ha^{-1} was the only treatment to provide less than 85% control of Palmer amaranth when the size was 2.5- to 7.5-cm tall (Table 2.8). The lack of a control with glyphosate was a result of the Palmer amaranth being from a resistant population. Isoxaflutole and tembotrione alone provided ≥ 94% control when applied alone in both 2010 and 2011 (Table 2.9). In 2010, the addition of glyphosate to either isoxaflutole or tembotrione did not increase glyphosate-resistant Palmer amaranth control over tembotrione or isoxaflutole alone when the plants were 2.5- to 7.5 cm. Reduced activity of glufosinate on small Palmer amaranth (< 7.5 cm) in 2010 can be attributed to reduced absorption due to a low relative humidity (38%) at application as shown by Coetzer et al (2001). At the larger sizes of Palmer amaranth, neither HPPD herbicides alone or in combination with glyphosate or glufosinate resulted in acceptable control. Since this research was conducted there has been a study that shows there is no antagonism from glufosinate and tembotrione at a 1x field rate when applied to 7-cm tall Palmer amaranth (Botha et al. 2014). Applications to Palmer amaranth plants larger than 25 cm, in either 2010 or 2011, resulted in insufficient levels of control. No herbicide or combination of herbicides in either year provided > 70% Palmer amaranth control when plants were at least 25 to 30 cm tall at application, except for glyphosate alone and in combination with isoxaflutole in 2011 on the glyphosate-susceptible biotype. Based on the Palmer amaranth control provided by the combination of glyphosate or glufosinate with each of HPPD herbicide it appears that combination may be antagonistic on Palmer amaranth because the levels of control with the combination are similar to the control when each herbicide was applied alone.

Barnyardgrass Control. Barnyardgrass control was only rated at the first timing application timing of 2.5- to 7.5-cm in 2010 and 2.5- to 10-cm in 2011 because of shading by Palmer amaranth at later timings. The year by treatment interaction was significant; therefore, data are presented by year. In 2010, isoxaflutole, tembotrione, isoxaflutole + glufosinate at both rates, isoxaflutole + glyphosate, and tembotrione + glufosinate at both rates provided ≥ 80% barnyardgrass control (Table 2.10). Glufosinate at either 450 or 595 g ha^{-1} did not provide more than 70% control. In 2011, all herbicide treatments provided 96 to 99% barnyardgrass control. Based on this research, isoxaflutole and tembotrione appear to be good postemergence options for controlling barnyardgrass if applications are made according to manufacturer's recommendations only.

Yellow Nutsedge and Hemp Sesbania Control. The year by treatment interaction for both yellow nutsedge and hemp sesbania was not significant; hence, data were pooled over years. There were no differences among herbicide treatments for yellow nutsedge or hemp sesbania control, with yellow nutsedge control ranging from 74 to 90% and hemp sesbania control ranging from 91 to 99% (Table 2.10). Hence, it is does not appear that the addition of tembotrione or isoxaflutole to glyphosate or glyphosate will improve yellow nutsedge or hemp sesbania control. However, it should be noted that mixing two mechanisms of action that provide effective weed control is a strategy that is commonly recommended to reduce the risk of herbicide resistance evolving (Norsworthy et al. 212). While no herbicide-resistant hemp sesbania has ever been documented, ALS-resistant yellow nutsedge was recently confirmed in Arkansas (Wilson 2010). Although all treatments provided adequate control, the additional HPPD-inhibiting mechanism-of-action could be integrated into many integrated pest management systems to help delay resistance.

Summary

The objectives of this research were to determine the length and degree of weed control with HPPD-inhibiting herbicides that could eventually be used in HPPD-resistant cotton and soybean as an alternative or additional mechanism of action for control of problematic and resistant weeds. Results showed that there are still multiple options for the effective control of some of the most problematic weeds of Arkansas row crops. Palmer amaranth, barnyardgrass, and hemp sesbania can be effectively controlled with the correct combination of herbicides and alternating mechanisms of action. Although the adoption rate of HPPD-resistant crops by producers remains to be seen, it is an effective option for control of both resistant and susceptible weeds if applied at the correct timing. When used in the correct manner and with the right combination of herbicides, HPPD inhibitors will bring an extra effective mechanism of action to crops to combat an ever increasing problem of herbicide resistance. While HPPD-inhibiting herbicides use is limited in Arkansas, the need for expanded use of these herbicides in more crops will help to mitigate current resistance challenges. The commercialization of HPPD-resistant crops will not be the sole answer to the problematic and resistant weeds currently inundating Arkansas production fields; however, it will be an option for producers who have been limited in their herbicide options.

Literature Cited

Anonymous (2011) Roundup POWERMAX® herbicide label for use on Roundup Ready Flex Cotton®. St. Louis, MO: Monsanto Technology LLC 3 p

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2011) Modeling the evolution of glyphosate resistance in barnyardgrass in Arkansas cotton. Summ of Arkansas Cotton Research 2011:26-29

Beckie HJ (2006) Herbicide-resistant weeds: Management tactics and practices. Weed Technol 20:793-814

Botha GM, Burgos NR, Gbur EE, Alcober EA, Salas RA, Scott RC. (2014) Interaction of glufosinate with 2,4-D, dicamba, and tembotrione on glyphosate-resistant *Amaranthus palmeri*. Amer Jour Exper Agri 4:427-442

Coetzer E, Al-Khatib K, Loughin TM (2001) Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. Weed Sci 49:1-13

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol 18:443-453

Dean WE (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J Seed Res 44:242-248

Dill GM, Jacob CA, Padgette SR (2008) Glyphosate-resistant crops: adoption, use and future considerations. Pest Manag Sci 64:326-331

Duke SO, Powles SP (2009) Glyphosate-resistant crops and weeds: Now and in the future. AgBioForum 12: 346-357

Grossmann K, Ehrhardt T (2007) On the mechanism of action and selectivity of the corn herbicide topramezone: A new inhibitor of 4-hydroxyphenylpyruvate dioxygenase. Pest Manag Sci 63:429-439

Heap I (2014) International survey of herbicide resistant weeds. http://www.weedscience.org. Accessed June 3, 2014

Holt JS, Orcutt DR (1991) Functional relationships of growth and competitiveness in perennial weeds and cotton (*Gossypium hirsutum*). Weed Sci 39:575-584

Horak MJ, Loughin TM (2000) Growth analysis of four Amaranthus species. Weed Sci 48:347-355

Keeley PE, Carter CH, Tullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199-204

Keeley PE, Thullen RJ (1991) Biology and control of black nightshade (*Solanum nigrum*) in cotton (*Gossypium hirsutum*). Weed Technol 5:713-722

Jha, P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Jordan DL, York AC, Griffin JK, Clay PA , Vidrine PR, Reynolds DB (1997) Assessing the practical importance of weed evolution: a research agenda. Weed Res 37:237-246

Mallory-Smith CA, Retzinger EJ Jr (2003) Revised classification of herbicides by site of action for weed resistance management strategies. Weed Technol 17:605-619

Nelson KA, Renner KA, Penner D (2002) Yellow nutsedge (*Cyprus esculentus*) control and tuber production with glyphosate and ALS-inhibiting herbicides. Weed Technol 16:512-519

Pallett KE, Cramp SM, Little JP, Veerasekaran P, Crudace AJ, Slater AE (2001) Isoxaflutole: the background to its discovery and the basis of its herbicidal properties. Pest Manag Sci 57:133-142

Reddy KN, Boykin JC (2010) Weed control and yield comparisons of twin- and single-row glyphosate-resistant cotton production systems. Weed Technol 24:95-101

Riar SR, Norsworthy JK, Steckel LE, Stephenson DO, Bond JA. (2013) Consultant perspectives on weed management needs in midsouthern United States cotton. Weed Technol 27:778-787

Scott RC, Boyd JW, Smith KL, Seldon G, Norsworthy JK. 2014. Recommended chemicals for weed and brush control. MP44. http//www.uaex.edu/publications/pdf/mp44/mp44.pdf. Accessed: July 25, 2014

Sellers BA, Smeda RJ, Johnson GW. 2003. Diurnal fluctuations and leaf angle reduce glufosinate efficiacy. Weed Technol 17:302-306.

Sosnoskie LM, Kichler JM, Wallace R, Culpepper AS (2009) Multiple resistance to glyphosate and an ALS inhibitor in Palmer amaranth in GA. p. 1351-1352. Proc Beltwide Cotton Conf

Stuebler H, Kraehmer H, Hess M, Shulz A, Rosinger C (2008) Global changes in crop production and impact trends in wed management – an industry view. Proc 5th Int Weed Sci Cong 1:309-319

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in major agronomic crops in the southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145-157

Wilson MJ, Norsworthy JK, Johnson DB, McCallister EK, Devore JD, Griffith GM, Banagarwa SK, Scott RC, Smith KL (2010) Herbicide programs for controlling ALS-resistant barnyardgrass in Arkansas rice. B. R. Wells Rice Research Series 581. Pp. 153 -157

Viviani F, Little JP, Pallet KE (1998) The mode of action of isoxaflutole II. Characterization of the inhibition of carrot 4-hydroxyphenylpyruvate dioxygenase by the diketonitrile derivative of isoxaflutole. Pestic Biochem Physiol 62:125-134

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307

Table 2.1. Soil properties from a 0- to 10-cm depth at Fayetteville, Keiser, and PineTree, Arkansas.

Location	Year	Sand	Silt	Clay	Soil organic matter	Soil texture	Soil pH
		$g\ g^{-1}$			%		
Fayetteville	2010	0.23	0.49	0.28	1.8	Silt loam	6.4
	2011	0.27	0.50	0.23	1.4	Silt loam	6.5
Keiser	2010	0.09	0.22	0.69	3.8	Clay	6.5
	2011	0.18	0.20	0.62	3.3	Clay	6.7
PineTree	2011	0.05	0.67	0.28	2.2	Silt loam	6.5

Table 2.2. Palmer amaranth control with residual herbicides at 4 and 8 wk after treatment (WAT) on a clay soil at Keiser, AR in 2010 and 2011.

		Palmer amaranth control[a]			
		2010		2011	
Herbicide treatment	Rate	4 WAT	8 WAT	4 WAT	8 WAT
	g ai ha $^{-1}$	%			
Isoxaflutole	105	93 a	75 cd	98 ab	69 ab
Tembotrione	92	94 a	82 abc	90 c	55 abc
Thiencarbazone + isoxaflutole	37 + 92	96 a	92 abc	100 a	89 ab
Mesotrione	210	96 a	80 bc	100 a	99 a
S-metolachlor	1784	99 a	89 abc	100 a	70 ab
Pendimethalin	1704	98 a	55 d	93 bc	23 c
Fomesafen	280	95 a	98 ab	93 bc	52 bc
Sulfentrazone + metribuzin	202 + 303	99 a	100 a	100 a	99 a
S-metolachlor + metribuzin	1987 + 473	99 a	100 a	100 a	97 a
S-metolachlor + fomesafen	1217 + 266	99 a	100 a	97 abc	66 ab
Flumioxazin	71	97 a	90 abc	100 a	73 ab
S-metolachlor + mesotrione	1873 + 185	95 a	99 a	100 a	99 a
Chlorimuron + flumioxazin + thifensulfuron	23 + 72 + 7	95 a	88 abc	100 a	93 a

[a] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

Table 2.3. Palmer amaranth control with residual herbicides at 2, 4, 6, and 10 wk after treatment (WAT) on a silt loam soil at Fayetteville, AR averaged over 2010 and 2011.

		Palmer amaranth control[a]			
Herbicide treatment	Rate	2 WAT	4 WAT	6 WAT	10 WAT
	g ai ha $^{-1}$	%			
Isoxaflutole	88	91 a	98 a	66 cd	74 abc
Tembotrione	92	90 ab	93 ab	55 d	55 c
Thiencarbazone + isoxaflutole	37 + 92	100 a	100 a	69 bcd	50 c
Mesotrione	210	100 a	100 a	82 abc	87 ab
S-metolachlor	1335	100 a	99 a	85 abc	85 ab
Pendimethalin	1119	79 b	86 b	77 abcd	56 c
Fomesafen	280	99 a	99 a	98 a	91 a
Sulfentrazone + metribuzin	151 + 227	96 a	99 a	91 ab	87 ab
S-metolachlor + metribuzin	1545 + 368	100 a	99 a	91 ab	88 ab
S-metolachlor + fomesafen	1217 + 266	100 a	100 a	99 a	92 a
Flumioxazin	71	99 a	99 a	93 ab	65 bc
S-metolachlor + mesotrione	1873 + 185	100 a	100 a	95 a	91 a
Chlorimuron + flumioxazin + thifensulfuron	23 + 72 + 7	99 a	99 a	94 ab	89 a

[a] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

Table 2.4. Late season Palmer amaranth density relative to the nontreated control as influenced by choice of residual herbicide in 2010 and 2011 at Keiser and Fayetteville, AR. [a]

		Palmer amaranth density[a]			
		Keiser (clay)		Fayetteville (silt loam)	
Herbicide treatment	Rate[b]	2010	2011	2010	2011
	g ai ha $^{-1}$	% of nontreated			
Isoxaflutole	105/88*	50 cde	13 cd	38 a	28 a
Tembotrione	92	100 a	40 ab	35 a	14 bc
Thiencarbazone + isoxaflutole	37 + 92	23 bcd	12 d	18 bc	8 d
Mesotrione	210	44 abc	7 d	7 d	32 a
S-metolachlor	1784/1335*	54 bcd	10 d	13 cd	7 d
Pendimethalin	1704/1119*	8 ef	44 a	24 b	8 d
Fomesafen	280	50 def	5 d	17 bcd	1 d
Sulfentrazone + metribuzin	202/151 + 303/227*	0 f	0 d	10 cde	11 c
S-metolachlor + metribuzin	1987/1545 + 473/368*	0 f	3 d	8 de	5 d
S-metolachlor + fomesafen	1217+266	4 ef	20 c	1 e	2 d
Flumioxazin	75	9 ef	0 d	4 e	17 bc
S-metolachlor + mesotrione	1873 + 185	8 def	1 d	6 e	11 c
Chlorimuron + flumioxazin + thifensulfuron	23 + 72 + 7	67 def	2 d	3 e	10 cd

[a] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD (P ≤ 0.05).
[b] '*' represents different rate for clay or silt loam soil texture where the higher rate is for the clay soil texture.

Table 2.5. Barnyardgrass control with residual herbicides at 4 and 8 wk after treatment (WAT) on a clay soil at Keiser, AR in 2010 and 2011.

		Barnyardgrass control[a]			
		2010		2011	
Herbicide treatment	Rate	4 WAT	8 WAT	4 WAT	8 WAT
	g ai ha $^{-1}$	%			
Isoxaflutole	105	55 bc	34 e	73 d	80 abc
Tembotrione	92	53 c	39 e	19 f	30 d
Thiencarbazone + isoxaflutole	37 + 92	72 abc	59 e	90 abc	97 ab
Mesotrione	210	75 abc	65 cde	86 abcd	99 a
S-metolachlor	1784	97 a	93 abcd	89 abcd	89 abc
Pendimethalin	1704	96 a	93 abcd	91 abc	40 d
Fomesafen	280	93 a	96 ab	40 e	60 bcd
Sulfentrazone + metribuzin	202 + 303	99 a	96 a	79 cd	98 a
S-metolachlor + metribuzin	1987 + 473	97 a	95 abc	95 a	99 a
S-metolachlor + fomesafen	1217 + 266	96 a	95 ab	83 bcd	60 dc
Flumioxazin	71	83 ab	68 bcde	80 bcd	81 abc
S-metolachlor + mesotrione	1873 + 185	94 a	93 abcd	91 ab	99 a
Chlorimuron + flumioxazin + thifensulfuron	23 + 72 + 7	61 bc	60 de	83 bcd	94 abc

[a] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

Table 2.6. Barnyardgrass control with residual herbicides at 2, 6, and 10 wk after treatment (WAT) on a silt loam soil in 2011 averaged over Fayetteville, AR and PineTree, AR.

Herbicide treatment	Rate	Barnyardgrass control[a] 2 WAT		6 WAT		10 WAT	
	g ai ha $^{-1}$	%					
Isoxaflutole	88	51	d	34	c	55	cd
Tembotrione	92	70	c	0	d	13	f
Thiencarbazone + isoxaflutole	37 + 92	98	a	94	a	91	a
Mesotrione	210	92	ab	29	c	30	ef
S-metolachlor	1335	99	a	90	a	83	a
Pendimethalin	1119	93	a	74	ab	59	bcd
Fomesafen	280	84	b	20	cd	16	f
Sulfentrazone + metribuzin	151 + 227	97	ab	73	ab	76	abc
S-metolachlor + metribuzin	1545 + 368	99	a	89	a	90	a
S-metolachlor + fomesafen	1217 + 266	100	a	98	a	90	a
Flumioxazin	71	97	ab	48	bc	50	de
S-metolachlor + mesotrione	1873 + 185	93	ab	85	a	79	ab
Chlorimuron + flumioxazin + thifensulfuron	23 + 72 + 7	94	ab	39	c	53	d

[a] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

Table 2.7. Percent of total barnyardgrass emergence as influenced by choice of residual herbicide at Keiser, AR in 2010 and 2011[b] and at Fayetteville and PineTree, AR in 2011.

		Barnyardgrass density (m^{-2})			
		clay[a]		silt loam[b]	
Herbicide treatment	Rate	Keiser		Fayetteville and PineTree	
	g ai ha $^{-1}$	%			
Isoxaflutole	105	86	ab	85	a-d
Tembotrione	92	100	a	81	a-d
Thiencarbazone + isoxaflutole	37 + 92	62	ab	53	d
Mesotrione	210	91	ab	72	bcd
S-metolachlor	1780	12	c	85	a-d
Pendimethalin	1700	16	c	55	cd
Fomesafen	280	9	c	100	a
Sulfentrazone + metribuzin	25 + 38	8	c	76	a-d
S-metolachlor + metribuzin	1990 + 473	17	c	92	ab
S-metolachlor + fomesafen	1220 + 266	13	c	100	a
Flumioxazin	71	62	b	50	a-d
S-metolachlor + mesotrione	1870 + 185	10	c	71	bcd
Chlorimuron + flumioxazin + thifensulfuron	23 + 72 + 7	73	ab	97	ab

[a] Barnyardgrass density was not assessed at Keiser in 2011.

[b] Barnyardgrass data statistically differed between soil textures but did not differ within soil textures using ANOVA; thus the silt loam locations data was pooled prior to analysis. Letters of separation were calculated by the counts of total barnyardgrass emergence at the end of the season. Means within a column followed by the same letter are not significantly different.

Table 2.8. Palmer amaranth control in 2010 at Fayetteville, AR with POST applications of herbicides at three timings.[a]

		Control					
		Plant height (cm)[b]					
Herbicide treatment	Rate	2.5 to 7.5		25 to 38		38 to 50	
	g ai or ae ha $^{-1}$	%					
Isoxaflutole	105	94	a	53	b-f	43	b-g
Tembotrione	92	98	a	62	b	35	d-g
Glufosinate	450	90	a	51	b-f	30	fg
Glufosinate	595	85	a	51	b-f	37	c-g
Glyphosate	860	33	fg	61	b	33	efg
Isoxaflutole + glufosinate	105 + 450	95	a	55	b-e	42	b-g
Isoxaflutole + glufosinate	105 + 595	99	a	48	b-f	25	g
Isoxaflutole + glyphosate	105 + 860	98	a	53	b-f	43	b-g
Tembotrione + glufosinate	92 + 450	96	a	56	bcd	49	b-f
Tembotrione + glufosinate	92 + 595	89	a	59	bc	38	c-g
Tembotrione + glyphosate	92 + 860	86	a	50	b-f	44	b-g

[a] Control was assessed at 3 wk after treatment for each herbicide application timing.
[b] Means across all plant height columns followed by the same letter did not differ significantly when using Fisher’s protected LSD ($P \leq 0.05$).

Table 2.9. Palmer amaranth control in 2011 with POST herbicides applied three timings.[a]

Herbicide treatment	Rate	Control					
		Plant height (cm)[b]					
		2.5-10		30-45		45-65	
	g ai or ae ha^{-1}	%					
Isoxaflutole	105	96	a	51	def	35	ef
Tembotrione	92	95	a	59	cde	58	def
Glufosinate	450	96	a	49	def	48	def
Glufosinate	595	97	a	51	def	36	ef
Glyphosate	860	100	a	88	ab	33	f
Isoxaflutole + glufosinate	105 + 450	99	a	52	def	60	cde
Isoxaflutole + glufosinate	105 + 595	99	a	38	ef	44	ef
Isoxaflutole + glyphosate	105 + 860	100	a	84	abc	36	ef
Tembotrione + glufosinate	92 + 450	100	a	50	def	48	def
Tembotrione + glufosinate	92 + 595	100	a	47	def	61	cde
Tembotrione + glyphosate	92 + 860	100	a	53	def	70	bcd

[a] Control was assessed at 3 wk after treatment for each herbicide application timing.

[b] Means within columns and across all plant height columns followed by the same letter did not differ significantly when using Fisher's protected LSD (P ≤ 0.05).

Table 2.10. Yellow nutsedge, barnyardgrass, and hemp sesbania control 3 wk after POST treatment at Fayetteville, AR.[a]

		Control					
		Barnyardgrass[b]				Yellow nutsedge[d]	Hemp sesbania[d]
Herbicide treatment	Rate	2010		2011			
	g ai/ae ha^{-1}	———		%		———	
Isoxaflutole	105	97	a	96	c	84	96
Tembotrione	92	88	ab	98	b	74	99
Glufosinate	450	69	bc	99	a	75	97
Glufosinate	595	26	d	99	a	80	91
Glyphosate	860	66	c	99	a	83	96
Isoxaflutole + glufosinate	105 + 450	96	a	99	a	87	99
Isoxaflutole + glufosinate	105 + 595	99	a	99	a	87	99
Isoxaflutole + glyphosate	105 + 860	99	a	99	a	87	99
Tembotrione + glufosinate	92 + 450	84	abc	99	a	90	99
Tembotrione + glufosinate	92 + 595	80	abc	99	a	89	98
Tembotrione + glyphosate	92 + 860	65	c	99	a	90	95

[a] Weed species of plants at application were 2.5 to 7.5 cm and 1 to 2 lf for all three species.
[b] The year by herbicide treatment interaction was significant for barnyardgrass control; hence, data are presented by year.
[c] Means are separated using Fisher's protected LSD ($P \leq 0.05$).
[d] Means for yellow nutsedge and hemp sesbania were not significant based on ANOVA (α=0.05).

Appendices

Appendix 2.1. Sources of materials for the experiment evaluating PRE-applied HPPD-inhibiting herbicide compared to current herbicide standards.

Herbicide	Trade Name	Formulation	Rate [a]	Manufacturer	Address	Website
		g ai L^{-1}	g ai ha^{-1}			
Isoxaflutole	Balance Flexx	240	88	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Tembotrione	Laudis	420	92	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Isoxaflutole +thiencarbazone methyl	Corvus	315	92 + 37	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
S-metolachlor	Dual Magnum	914	1335/1784	Syngenta	Greensboro, NC	http://www. sygenta.com/
Pendimethalin	Prowl H20	456	1119/1704	BASF Corporation	Fordham, NJ	http://agro.basf.com/
Fomesafen	Reflex	240	280	Syngenta	Greensboro, NC	http://www. sygenta.com/
Sulfentrazone + metribuzin	Authority MTZ	450[b]	151/202 + 227/303	FMC Agricultural	Philadelphia, PA	http://www.fmccorp.com
S-metolachlor + metribuzin	Boundary	780	1545/1987 + 368/473	Syngenta	Greensboro, NC	http://www. sygenta.com/
S-metolachlor + fomesafen	Prefix	635	1217 + 266	Syngenta	Greensboro, NC	http://www. sygenta.com/
Mesotrione	Callisto	480	210	Syngenta	Greensboro, NC	http://www. sygenta.com/
Flumioxazin	Valor	510[b]	71	Valent Corporation	Walnut Creek, CA	http://www.valent.com/
S-metolachlor + mesotrione	Camix	440	1873 + 185	Syngenta	Greensboro, NC	http://www. sygenta.com/
Chlorimuron ethyl + flumioxazin + thifensulfuron methyl	Envive	413[b]	23 +72 + 7	DuPont	Wilmington, DE	http://www.dupont.com/

[a] Rates are broken out by soil texture when more than one rate is listed. The low rate was used on the silt loam soil texture.
[b] Rates are in g ai kg^{-1}.

Appendix 2.2. Sources of materials for the experiment evaluating POST-applied HPPD-inhibiting herbicides alone and in combination with glufosinate or glyphosate.

Herbicide	Trade Name	Formulation	Rate	Manufacturer	Address	Website
			g ai ha^{-1}			
Isoxaflutole	Balance Flexx	240	88	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Tembotrione	Laudis	420	92	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Glufosinate	Ignite	280	450/595	Bayer CropScience	Research Triangle Park, NC	http://www.bayercropscience.us/
Glyphosate	Roundup WeatherMax	540	580[a]	Monsanto Company	St. Louis, MO	http://www.monsanto.com/
Methylated seed oil	MSO		1%	Helena Chemical Co.	Collierville, TN	http://www.helenachemical.com/

[a] Glyphosate rate is reported as g ae ha^{-1}

Conclusions

The majority of the spread of herbicide-resistant *Echinochloa* spp. is limited to propanil and quinclorac, which were discovered and confirmed resistant in 11 counties in Arkansas. There are still viable options to control these problematic weeds in rice production across the area sampled as clomazone, imazethapyr, and fenoxaprop were all viable options for control. The preservation of these herbicide technologies can be well maintained for years to come by the use of cultural, mechanical, and alternating chemical control practices. When three of the four most troublesome weeds in Arkansas have expressed resistance to more than one mechanism of action, there is a strong need for change and new tools.

The commencement of the glyphosate era has produced a slowdown in the terms of herbicide and trait discovery so much that there are very few chemical options in the industry pipeline. The HPPD-inhibiting herbicides are one of the latest mechanism of action available to producers. Currently, the HPPD-inhibitors will not provide the length of residual control equal to that of current industry standards; however isoxaflutole, tembotrione, and mesotrione are all capable of producing up to 4 weeks of residual control of Palmer amaranth. Preemergence application of HPPD-inhibiting herbicides for barnyardgrass was less than the industry standards. When there is an alternative mechanism of action (ie. thiencarbazone-methyl or *S*-metolachlor) in combination with the HPPD-inhibitors, length of residual barnyardgrass control is increased. POST applications of HPPD-inhibitors must be made to weeds less than 10 cm tall. This will allow for through coverage in dense canopies of weeds. Yellow nutsedge, hemp sesbania, and barnyardgrass (2011) were all effectively (>90%) controlled as long as the environmental conditions were conducive for glufosinate and spray coverage was not an issue. When the weed size increased to greater than 25 cm, no HPPD herbicide provided acceptable control of glyphosate-resistant Palmer amaranth.